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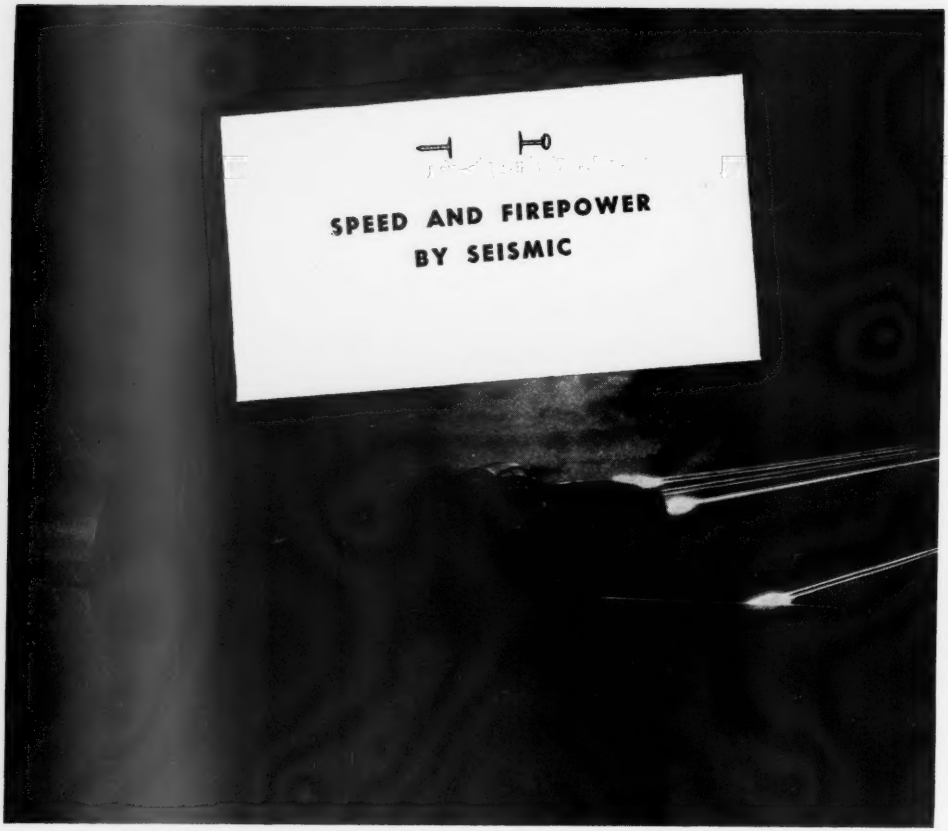

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MARINE MICROÖRGANISMS WHICH OXIDIZE PETROLEUM HYDROCARBONS[1]

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ABSTRACT

Bacteria are found in the sea which are capable of utilizing petroleum ether, gasoline, kerosene, lubricating oils, crude oils, petrolatum, paraffine wax, mineral oil, methane, pentane, hexane, decane, trimethylpentane, tetratriacontane, benzene, xylene, toluene, cyclohexane, anthracene, naphthalene, and other hydrocarbons. Sea water from the euphotic zone contains 10 to 1,000 hydrocarbon-oxidizing bacteria per liter, and 100 to 100,000 such bacteria have been found per gram of recent marine sediments. All samples of sediments regardless of distance from land, water depth, or core depth have shown the presence of hydrocarbon-oxidizing bacteria. Most of the bacteria oxidize hydrocarbons only in the presence of free oxygen although some of them can utilize nitrate as a hydrogen acceptor. Possibly some of them can activate sulphate as a hydrogen acceptor. Hydrogen sulphide in concentrations exceeding 0.0001 mol per liter inhibits the bacterial oxidation of petroleum hydrocarbons.

Within certain limits long-chain hydrocarbons are oxidized more readily than those of smaller molecular weight, and aliphatic compounds are more susceptible to bacterial oxidation than cyclic or aromatic hydrocarbons. Compounds with unsaturated bonds are attacked more readily than saturated compounds. Carbon dioxide, methane, organic acids, and bacterial protoplasm are among the products resulting from the bacterial utilization of petroleum hydrocarbons. Species of *Proactinomyces*, *Actinomyces*, *Pseudomonas*, *Micromonospora*, *Mycobacterium*, and possibly other genera of marine microörganisms are able to oxidize hydrocarbons.

Although the reaction will take place in an aqueous system, the presence of sand, silt, diatomaceous earth, and other inert adsorbents accelerates the bacterial oxidation of hydrocarbons. Samples of crude oil added to marine sediments are rapidly destroyed under aerobic conditions. The activity of hydrocarbon-oxidizing bacteria, which appear to be widespread in occurrence, may account for the failure of certain workers to find petroleum hydrocarbons in sediment samples. Similarly such bacteria might prevent the accumulation of detectable quantities of hydrocarbons in experiments with mixed cultures designed to demonstrate the transformation of organic matter into hydrocarbons. Our work suggests that one might expect to find oil accumulating in recent sediments or in experimental material only if conditions are inimical to the activity of hydrocarbon-oxidizing bacteria.

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INTRODUCTION

Following the isolation and description of bacteria which oxidize methane to carbon dioxide and water (Söhngen, 1906), the work of Giglioli and Masoni (1911, 1917) showed that methane-oxidizing bacteria abound in manure, ditch mud, sewage, and other environments where methane is being produced. Bacteria which attack higher hydrocarbons have been found in soil by Söhngen (1913), Wagner (1914), Tausz and Peter (1919), Büttner (1926), Gray and Thornton (1928), Stone *et al.* (1942), and others.

Although they may not require hydrocarbons for their growth, bacteria which can utilize hydrocarbons seem to occur most abundantly in oil-soaked soil (Baldwin, 1922; Tauson, 1929; Haas *et al.*, 1941; Johnson *et al.*, 1942). Hydrocarbon-oxidizing bacteria have also been found in crude oil by Lipman and Greenberg (1932), Tauson and Shapiro (1934), Wakengut (1936), and Bushnell and Haas (1941), and in storage-tank water by Thaysen (1939) and Bushnell and Haas (1941). Additional literature on the occurrence and activity of hydrocarbon-oxidizing bacteria has been summarized by Hessel (1924), Tauson (1929), and Haas (1942).

Judging from the extensive occurrence of hydrocarbon-oxidizing bacteria in other environments, one might expect to find such bacteria in the sea and particularly in unconsolidated sedimentary materials. If present and functional, such bacteria might preclude the possibilities of finding hydrocarbons in detectable quantities even if the hydrocarbons are being deposited or produced by the transformation of organic matter. Because of the important rôle that they may play in the problem of petroleum genesis, an extensive investigation is being made on the factors which influence the distribution and activity of hydrocarbon-oxidizing bacteria in the sea. The following report summarizes some preliminary observations.

EXPERIMENTAL METHODS

The disappearance or emulsification of petroleum hydrocarbons, the growth of bacteria in mineral media containing hydrocarbons as the only source of energy, and the estimation of the amount of oxygen consumed or carbon dioxide produced are the methods most commonly used to study the activity of hydrocarbon-oxidizing bacteria. We have found oxygen consumption, occasionally supplemented by other methods, most suitable for obtaining information on the occurrence and behavior of hydrocarbon-oxidizing bacteria in the sea.

To demonstrate the presence of hydrocarbon-oxidizing bacteria, aseptically collected sea water was thoroughly shaken to insure uniformity in its composition including its dissolved oxygen content, after which it was siphoned into 60-ml. glass-stoppered bottles. Then 0.1 ml. of sterile liquid hydrocarbon was introduced with a pipette while the bottle was being held in such a way that the hydrocarbon would be entrapped in the shoulder of the bottle until the glass stopper could be inserted. The dissolved oxygen content of duplicate pairs of such bottles was determined immediately using the Winkler technique, and the others were

analyzed after 10 to 20 days of incubation in a water bath at 22°C. Sterilized water was bottled in the same way to serve as a control.

The protocol of a representative experiment is summarized in Table I. The fact that considerably more oxygen was consumed in the bottles filled with raw (unsterilized) sea water treated with hydrocarbons than in sterile controls or in the raw sea water to which no hydrocarbon was added indicates that hydrocarbon-oxidizing bacteria were present in the raw sea water. Oxygen consumption was accompanied by a marked increase in the bacterial population as shown by plate counts. From the plates of nutrient medium hydrocarbon-oxidizing bacteria could be isolated.

TABLE I

AMOUNT OF OXYGEN CONSUMED IN RAW (UNSTERILIZED) AND STERILE SEA WATER IN PRESENCE OF 0.15 PER CENT OF DIFFERENT PETROLEUM HYDROCARBONS AFTER 20 DAYS INCUBATION AT 22°C.

Hydrocarbon	*Sea Water*	*Initial Dissolved Oxygen Content (Mgm./l.)*	*Dissolved Oxygen after 20 Days (Mgm./l.)*	*Oxygen Consumed in 20 Days (Mgm./l.)**
Kerosene	Raw	6.46	0.14	6.32
Kerosene	Sterile	6.27	6.25	0.02
Paraffine oil	Raw	6.52	1.43	5.09
Paraffine oil	Sterile	6.20	6.16	0.04
Crude oil	Raw	6.41	0.00	6.41
Crude oil	Sterile	6.32	6.18	0.14
Petroleum ether	Raw	6.54	0.29	6.25
Petroleum ether	Sterile	6.31	6.23	0.08
None (control)	Raw	6.48	5.02	1.46
None (control)	Sterile	6.26	6.23	0.03

* Mgm./l. (milligrams per liter) is the same as p. p. m. (parts per million).

By use of similar experimental procedures it was found that all 60-ml. samples of sea water collected in the La Jolla region contain bacteria which can utilize kerosene, paraffine oil, crude oil (Kern County), and petroleum ether. The vertical distribution of hydrocarbon-oxidizing bacteria in the sea has not been studied yet. According to ZoBell and Anderson (1936), the bacterial population of the sea decreases rapidly with the depth of the water from a few hundred bacteria per ml. at the surface to fewer than 10 per ml. at depths exceeding 200 meters until the sea bottom is reached. Water from the bottom of the sea ordinarily contains thousands to millions of bacteria per ml., and marine sediments also contain large numbers of bacteria (ZoBell, 1938).

They are most abundant in the topmost portions of cores at the mud-water interface where from 100 to 100,000 hydrocarbon-oxidizing bacteria have been demonstrated per gram of sediment (wet basis). Their abundance decreases exponentially with depth reminiscent of the vertical distribution of bacteria in general (ZoBell and Anderson, 1936). Some have been found in the bottom of the longest core examined, it being about 17 feet in length. The samples were collected from the Channel Island region off the coast of Southern California and from the Gulf of California. The studies include samples collected from water depths as great as 12,370 feet. Large numbers of hydrocarbon-oxidizing bacteria have also been found in mud from Mission Bay (ZoBell and Feltham, 1942), Cardiff Slough, and San Diego Bay.

KINDS OF HYDROCARBONS ATTACKED

Besides kerosene, paraffine oil, crude oil, and petroleum ether which were used in the exploratory experiments, several other petroleum products are oxidized by bacteria isolated from the sea. Gasoline, lubricating oils of different viscosities, Shell-solvent, petrolatum, paraffine wax, and six different samples of California crude oils have been found to promote the multiplication and respiration of marine bacteria. While these substances contain impurities which might promote bacterial multiplication, the disappearance of oil globules and the stoichiometric consumption of oxygen and the production of carbon dioxide indicate that the substances are utilized almost quantitatively. Several chemically pure hydrocarbons have been used with similar results.

Table II shows the amount of oxygen consumed by mixed cultures of marine bacteria in aged sea water treated with approximately 0.1 per cent of different pure hydrocarbons. The sea water was aged for several weeks in the dark to permit bacteria to oxidize the organic matter normally present in recently collected sea water. It was inoculated with an enrichment culture of hydrocarbon-oxidizing bacteria. The experiment shows that all of the hydrocarbons are attacked by bacteria.

TABLE II

OXYGEN CONSUMED BY MIXED CULTURES OF MARINE BACTERIA IN PRESENCE OF DIFFERENT HYDROCARBONS IN AGED SEA WATER AFTER 14 DAYS INCUBATION AT 22°C.

Hydrocarbon	*Initial Dissolved Oxygen Content (Mgm./l.)*	*Dissolved Oxygen after 14 Days (Mgm./l.)*	*Oxygen Consumed in 14 Days (Mgm./l.)*
n-Hexane	6.68	0.00	6.68
Cyclohexane	6.71	6.27	0.44
Benzene	6.64	6.51	0.13
Xylene	6.40	0.00	6.40
Toluene	6.60	3.48	3.12
Anthracene	6.69	6.10	0.59
Naphthalene	6.68	0.00	6.68
Pyridine	6.64	2.66	3.98

Although oxygen is consumed very slowly in the presence of cyclohexane, benzene, and anthracene, repeated experiments prove that these compounds are definitely oxidized by bacteria. There are other factors besides the chemical composition of the various hydrocarbons such as their solubilities and dispersion in sea water which influence the rate at which they are utilized. As elaborated in succeeding pages, experiments with otherwise inert adsorbents are in progress on methods of providing for the comparable dispersion of hydrocarbons in aqueous systems.

Besides the hydrocarbons listed in Table II, it has been found that marine bacteria also oxidize methane, n-pentane, pentene, n-heptane, n-octane, trimethylpentane, n-decane, dotriacontane (dicetyl), tetratriacontane, isoprene, and neoprene. Narrow cuts of paraffine waxes having melting points ranging from 45°C. to 75°C. have also been used. ZoBell and Grant (1942) have found marine bacteria which oxidize the hydrocarbons of natural and synthetic rubber.

It appears that, in general, aliphatic compounds are attacked by bacteria more readily than aromatic or cyclic compounds. Within certain limits the longer the chain, the more readily it is attacked by bacteria. For example, when uniformly distributed in the water on sand grains, paraffine wax (probably C_{40} to C_{46}) is oxidized faster by bacteria than is tetratriacontane (C_{34}), and the latter is oxidized faster than n-heptane (C_7) or n-hexane (C_6). Also, it might be significant that petrolatum and lubricating oils are oxidized faster than kerosene, and kerosene is oxidized faster than gasoline. The oxidizability also seems to be a function of the number of side-chains, iso-octane, or trimethylpentane, being oxidized faster than n-octane. Whether these generalizations will continue to maintain when large numbers of pure hydrocarbons have been tested under truly comparable conditions remains to be seen.

Haag (1926) found that the higher the iodine number of paraffine waxes the more readily they were utilized by mycobacteria, thereby leading him to conclude that unsaturated bonds in molecules are attacked preferentially. This may explain why paraffine wax, petrolatum, and lubricating oils are oxidized faster than saturated compounds such as hexane and heptane as noted. On the other hand impurities in the paraffine wax, petrolatum, lubricating oils, kerosene, and gasoline might influence the results.

In spite of differences in the dispersion of hydrocarbons in aqueous media, Söhngen (1913a) noted that as a rule those having a boiling point above 150°C. were assimilated more readily by soil bacteria than those having a lower-boiling point. Strawinski and Stone (1940) have found that hydrocarbons in the range of 10 to 16 carbon atoms per molecule are attacked more readily than those of smaller weight. Tausz and Peter (1919) described a "Paraffine bacterium" isolated from soil which utilized hexadecane (C_{16}), triacontane (C_{30}) and tetratriacontane (C_{34}) but had little or no effect on the lower paraffines, n-hexane, and n-octane, or on benzene or naphthalene derivatives.

Bacterium aliphaticum (Tausz and Peter, 1919) had no effect on cyclic hydrocarbons, but it attacked all aliphatic compounds tried including n-hexane, n-octane, dimethyloctane, n-hexadecane, triacontane, and tetratriacontane. *Bact. aliphaticum* was unable to attack hexylene but it did attack the higher olefines, n-caprylene and hexadecylene. Certain cultures of Tausz and Peter (1919) utilized cyclohexane and dimethylcyclohexane. Johnson *et al.* (1942) found that *Bact. aliphaticum* grew well on pentane, hexane, heptane, octane, nonane, and dodecane. It grew only slightly on methylcyclohexane and not at all on benzene, toluene, or xylene.

According to Lantzsch (1922), *Actinomyces oligocarbophilus* could assimilate higher aliphatic hydrocarbons but not the lower ones, and it could not assimilate the aromatic compounds, benzene and xylene. However, it is not to be construed that the lower hydrocarbons are not assimilated by any bacteria because the work of Kaserer (1906), Störmer (1908), Münz (1920), Aiyer (1920), and others shows that certain bacteria oxidize methane. Söhngen (1906) isolated and described

Bacillus methanicus which is now called *Methanomonas methanica* (Bergey *et al.*, 1939). Recently G. David Novelli, working in the Scripps laboratories, has demonstrated the presence of methane-oxidizing bacteria in marine sediments.

Goobin (1923) described *Bacterium hidium* which oxidizes ethane, and an ethane-oxidizing bacterium, *Bacillus ethanicus*, is mentioned by Blau (1942). The methane-oxidizing bacterium of Tausz and Donath (1930) also utilizes ethane, propane, butane, and othe ons higher in the series more readily as the length of the chain increase er generalization applies to most of the cultures observed by Tausz nath. They studied another bacterium which could utilize only those hyd ns having more than 16 carbon atoms per molecule.

Although cyclic hydrocarbons are more refractory to bacterial attack than aliphatic compounds, many bacteria which utilize aromatic compounds have been described. Tauson (1929) described *Bacterium benzoli*, *Bact. toluolicum*, *Bact. naphthalinicus*, and *Bact. phenanthrenicus* which utilize benzene, toluene, xylene, anthracene, and phenanthracene. *Bacillus hexacarbovorum*, isolated from soil by Störmer (1908), oxidizes toluene and xylene as well as methane. The soil bacteria of Strawinski and Stone (1940) attack naphthalene, biphenyl, alpha-methyl-naphthalene, tetralin, tertiary butylbenzene, decalin, n-butylbenzene, and iso-butylbenzene, the oxidizability being in the order named. They were unable to develop a culture which was capable of growing on benzene or toluene. Some of their bacteria could grow on cetane, 1-octene, and 2-octene. Tausson (1927) has made a special study of the bacterial oxidation of naphthalene as well as of the bacteria which oxidize phenanthrene (Tausson, 1928b).

The writers have found that although toluene inhibits the growth of most microörganisms, including some of the hydrocarbon-oxidizing bacteria, bacteria occur in marine materials which grow freely in the presence of toluene. Most of the toluene, which is virtually insoluble in water, floats on the surface of the media. Oxygen consumption and an increase in the bacterial population in mineral media containing toluene as the only energy source indicates that toluene is oxidized by certain marine bacteria. Toluene is not attacked as readily as many other kinds of hydrocarbons investigated, and the bacteria which attack it are less abundant in marine materials than those which attack long straight-chain compounds.

Similar observations have been made on phenol. One per cent phenol kills most bacteria in a few minutes at room temperature and 0.1 per cent phenol ordinarily inhibits their growth. However, a few marine bacteria have been observed which multiply in the presence of 1.0 per cent phenol in peptone media. Some of them multiply in mineral media containing 0.1 per cent phenol as the only energy source. Cresol-oxidizing bacteria have also been demonstrated in marine materials.

Gray and Thornton (1928) found bacteria to be widely distributed in soil, which oxidize toluene, phenol, o-cresol, m-cresol, p-cresol, phloroglucinol, and

resorcinol. They found species of *Micrococcus*, *Mycobacterium*, *Bacterium*, *Bacillus*, and *Spirillum* which decompose aromatic compounds. Erikson (1941) studied *Micromonospora* species from lake mud, which utilize toluene, phenol, resorcinol, m-cresol, β-naphthol, naphthalene, and paradichlorobenzene. The observation that certain bacteria tolerate or utilize these hydrocarbons or hydrocarbon-derivatives is emphasized because the latter have been erroneously credited with preventing bacterial activity in oil deposits.

KINDS OF MICROÖRGANISMS

Most of the hydrocarbon-oxidizing microörganisms isolated from marine enrichment cultures have been proved to be species of *Proactinomyces*, *Actinomyces*, *Pseudomonas*, *Micromonospora*, or *Mycobacterium*. The writers have isolated four species of *Proactinomyces* from hydrocarbon cultures and, judging from colonial characteristics on plates of nutrient agar, several more species occur in marine materials. *Proactinomyces* are filamentous, mold-like bacteria which are differentiated from *Actinomyces* by the former's inability to form spores in the aerial mycelium. According to Umbreit (1939), many soil *Proactinomyces* are able to oxidize petroleum hydrocarbons. Five to 10 per cent of the microörganisms isolated from marine bottom sediments are *Proactinomyces*, but tests have not been made yet to determine how many of them utilize hydrocarbons.

Very few *Actinomyces* have been found in the sea at stations remote from the possibilities of terrigenous contamination, but those which have been isolated oxidize hydrocarbons. Hydrocarbons are oxidized by many terrestrial *Actinomyces* including *A. elastica* and *A. fascus* (Söhngen and Fol, 1914), *A. oligocarbophilus* (Lantzsch, 1922), *A. chromogenes albus*, *A. bovis*, *A. eppinger*, and *A. trautwein* (Büttner, 1926).

Two new species of *Pseudomonas* which oxidize hydrocarbons have been isolated from the sea. It is believed that several other marine species now under observation will likewise be proved to be *Pseudomonas*. Among the hydrocarbon enrichment cultures from terrestrial sources studied by Haas *et al.* (1941) and Stone *et al.* (1942) *Pseudomonas* species predominated. Bushnell and Haas (1941) found that *Ps. aeruginosa* oxidized hydrocarbons, and Johnson *et al.* (1942) observed the utilization of various petroleum hydrocarbons by *Ps. fluorescens*.

Several species of *Mycobacterium* have been found in marine sediments, at least two of which can utilize hydrocarbons as the sole source of carbon and energy. Söhngen (1913a) found that hydrocarbons are oxidized by *Mycobacterium album*, *M. lacticola*, *M. luteum*, *M. phlei*, *M. rubrum*, and *M. hyalinum*. Baldwin (1922) isolated *M. hyalinum* from soil soaked with crude oil. *Mycobacterium* species were ordinarily present in the cultures isolated from oil-soaked soil by Haas *et al.* (1941). Haag (1927) found that the ability of certain species of *Mycobacterium* to utilize hydrocarbons could be used to differentiate them from other bacteria.

Besides the aforementioned genera, bacterial species belonging to each of the

following genera have been credited with the ability to oxidize petroleum hydrocarbons: *Bacillus*, *Bacterium*, *Corynebacterium*, *Micrococcus*, *Sarcina*, *Serratia*, and *Spirillum*. Certain molds are also endowed with the ability to oxidize hydrocarbons (Rahn, 1906). Hopkins and Chibnall (1932) have studied the growth of *Aspergillus versicolor* on higher paraffines, and Tauson (1929) noted the growth of *Aspergillus flavus* and a species of *Penicillium* on hydrocarbons. Tauson (1939) found that several yeasts or yeast-like organisms including species of *Debaryomyces*, *Endomyces*, *Hansenia*, *Monilia*, and *Torolopsis* could utilize petroleum hydrocarbons.

These examples should suffice to show that the ability to oxidize petroleum hydrocarbons is very widespread among microörganisms.

EFFECT OF OXYGEN

Virtually all of the results of the microbial oxidation of petroleum hydrocarbons have been obtained with the microörganisms growing in the presence of free oxygen. Whether there are bacteria which can oxidize hydrocarbons under strictly anaerobic conditions is still unknown although there are indications that the reaction can take place in the presence of nitrate, sulphate,[4] and possibly other hydrogen acceptors.

The writers have noted the growth of bacteria and the reduction of nitrate in mineral media containing various hydrocarbons as the sole source of energy. However, this reaction is of little practical significance in source sediments because, as a general rule, if there is no free oxygen in sediments, there will be no nitrate. In fact, nitrate ordinarily disappears before all of the free oxygen is consumed in marine bottom deposits. Thaysen (1939) and Bushnell and Haas (1941) have noted the reduction of nitrate by hydrocarbon-oxidizing bacteria. According to Tausson (1928) *Bacterium benzoli* utilized about 8 grams of benzene in 42 days in the presence of nitrates.

The occurrence of sulphate-reducing bacteria in crude oil and oil-well brines (Bastin, 1926, Gahl and Anderson, 1928, Ginter, 1930, Bastin and Greer, 1930) has been interpreted by some to suggest that sulphate may provide the oxygen for the oxidation of petroleum hydrocarbons. Bacteria which reduce sulphate in the presence of manufactured gas were reported by Kegal (1940), and there is an anonymous (1938) report that certain kerosene-oxidizing bacteria reduce sulphate. Seliber (1928) studied sulphate-reducing bacteria which could obtain their energy requirements from the decomposition of grease and olive oil. The oxidation of crude oil accompanied by the reduction of sulphate by *Vibrio aestu-*

[4] Recently Dr. Haas has demonstrated repeatedly the anaerobic utilization of paraffine oil, kerosene, decane, tetradecane, and cetane by bacteria growing in sulphate media. Ferrous iron was used in the media to combine with the hydrogen sulphide as fast as it was formed from the reduction of the sulphate. The hydrocarbon was adsorbed on ignited sand in order to make it more available to the anaerobic bacteria which grow at the bottom of the media. The observation has been confirmed by G. David Novelli.

ari has been reported by Maliyantz (1935) as a means of desulphurizing Russian crude oils, but the bacteria might have been utilizing non-hydrocarbon constituents of the crude oils for energy.

In the exploratory experiments conducted by McCoy and Keyte (1934), they observed the bacterial oxidation of crude oil in a sulphate medium under anaerobic conditions. According to Beckman (1926) bacteria from oil-soaked soil grew under both aerobic and anaerobic conditions in a petroleum distillate having a boiling point of 232°C. Baier (1937) envisions sulphate-reducing bacteria growing in the oil-water interface of petroleum deposits where the bacteria might be able to obtain their energy from the oxidation of crude-oil constituents and their oxygen requirements from sulphate, but he admits conclusive evidence is lacking.

In characterizing oil-field waters, Smith (1931) points out that, with few exceptions, waters associated with oil contain little or no sulphate, which he attributes to sulphate reduction. However, this fails to prove that bacteria are responsible for the reduction of the sulphate, and even if they are, fatty acids and other non-hydrocarbon organic constituents may have served as an energy source. Baars (1930) found that while sulphate-reducing bacteria might utilize certain constituents of crude oil, neither *Vibrio desulfuricans* nor *V. rübentschickii* could utilize pure hydrocarbons. None of a limited number of hydrocarbons was utilized by *Vibrio aestuari*, the marine sulphate-reducer studied by Rittenberg (1941).

The writers have many cultures incubating under different conditions in an effort to ascertain if bacteria exist which can obtain their oxygen requirements from sulphate for the oxidation of petroleum hydrocarbons. Both *Bacterium aliphaticum* and *Vibrio desulfuricans* produce a slight turbidity in sulphate media enriched with either paraffine oil, kerosene, n-hexane, or cyclohexane in an anaerobic environment, but there has been no production of sulphide to indicate sulphate reduction.[4]

It does not seem probable that sulphate can be reduced by hydrocarbon-oxidizing bacteria since, as is elaborated later, hydrogen sulphide is inhibitory. However, the sulphate might be reduced without hydrogen sulphide accumulating in toxic concentrations, the sulphide might be precipitated from solution by heavy metals, or sulphate might be reduced to free sulphur. Conclusions must be withheld until experimental results are available on many more cultures investigated under conditions designed to simulate those which might occur in nature.

Unquestionably free oxygen promotes the activity of the hydrocarbon-oxidizing bacteria which we have isolated from the sea, although the oxygen tension does not seem to be important provided some free oxygen is present. The bacteria begin to grow with equal facility at any oxygen tension tested from a partial oxygen pressure of 12 to 408 mm. of mercury. When only a little oxygen is present, it is quickly consumed after which bacterial multiplication is retarded or stops. If the medium is saturated with oxygen, the hydrocarbon-oxidizing bac-

teria continue to multiply until all of the oxygen is consumed. This confirms the observations of ZoBell (1940) on the effect of oxygen tension on the rate of oxidation of organic matter by marine aerobes.

EFFECT OF SULPHIDE

The use of enrichment cultures of sulphate-reducing bacteria containing hydrogen sulphide inhibited the oxidation of hydrocarbons by known hydrocarbon oxidizers even under aerobic conditions. This has been attributed to the inhibiting effect of sulphide which is indicated by the data in Table III. Concentrations of sodium sulphide ranging from M/1000 to M/100,000 were added to sea water inoculated with a mixed culture of hydrocarbon-oxidizing bacteria and treated with 0.1 per cent paraffine oil. The oxygen content of the water was determined at the beginning of the experiment and again after different periods of incubation in a water bath at 22°C.

TABLE III

OXYGEN CONSUMED IN 21 DAYS AT 22°C. BY MARINE BACTERIA IN SEA WATER ENRICHED WITH 0.1 PER CENT OF PARAFFINE OIL AND TREATED WITH DIFFERENT CONCENTRATIONS OF SODIUM SULPHIDE

Amount of Sodium Sulphide Added (Mols./l.)	*Initial Dissolved Oxygen Content (Mgm./l.)*	*Dissolved Oxygen after 21 Days (Mgm./l.)*	*Oxygen Consumed in 21 Days (Mgm./l.)*
None (control)	6.84	0.03	6.81
0.000,01	7.10	0.88	6.02
0.000,1	7.08	4.73	2.35
0.001	3.26	3.12	0.14

From the data in Table III it may be observed that there was no bacterial activity in the sea water containing M/1000 sodium sulphide, and M/100,000 sodium sulphide was definitely inhibitory. It has been established that the toxic effect is due to the sulphide ion and not to changes in the hydrogen-ion concentration caused by the addition of sodium sulphide. It was necessary to make the water slightly acid in reaction (pH 6.5) by the addition of hydrochloric acid to prevent the sulphide from combining with oxygen. Under these conditions most of the sulphide occurred as hydrogen sulphide. Controls showed that a pH as low as 6.0 does not inhibit marine hydrocarbon-oxidizing bacteria. Hydrogen sulphide is not compatible with oxygen in an alkaline medium.

Whether or not sulphide will be proved to inhibit the oxidation of hydrocarbons under various conditions remains to be seen. According to Elvehjem *et al.* (1941) hydrogen sulphide in concentrations as low as M/2500 inhibits the activity of some oxidases although other oxidases are affected little or not at all. They report that certain oxidases are also inhibited by cyanide, azide, carbon monoxide, fluoride, arsenite, selenite, heavy metals, hydroxylamine, and other compounds. Johnson *et al.* (1942) noted that the bacterial oxidation of octane and nonane was inhibited by 0.000,08 M. cyanide or by 0.25 M. urethane.

The fact that there are substances which inhibit the bacterial oxidation of hydrocarbons suggests that there may be marine environments where hydro-

carbons are not attacked by bacteria although such bacteria appear to be widely distributed. On the sea floor one might expect to find significant concentrations of sulphide, carbon monoxide, heavy metals, and maybe other oxidase inhibitors. A detailed study of substances or conditions which inhibit the bacterial oxidation of hydrocarbons is contemplated.

EFFECT OF SURFACE

Most petroleum hydrocarbons are virtually insoluble in water. Consequently they must be attacked by bacteria primarily at the oil-water interface. Anything which tends to increase the dispersion of hydrocarbons in an aqueous system should accelerate their utilization. This has been demonstrated with paraffine wax. When 0.1 gram of wax in one small cube was placed in a bottle of inoculated sea water, 0.32 mgm./l. of oxygen was consumed in 10 days, but when the same quantity of wax was introduced in the form of thin shavings, 1.47 mgm./l. of oxygen was consumed during the same period. When 0.1 gram of paraffine wax was dispersed in the water by mixing 20 grams of ignited sand with molten wax, all of the oxygen (7.46 mgm./l.) was utilized in 10 days.

Attempts have been made to disperse other kinds of petroleum hydrocarbons with the use of biologically inert substances including ignited marine sediment, sand, bentonite, asbestos fibers, and infusorial earth. Table IV illustrates the effect of a sample of marine sediment (a red clay from the Pacific) on the bacterial oxidation of various hydrocarbons. Approximately 20 grams of the sediment (ignited to destroy oxidizable organic matter) were measured into each of several 160-ml. glass-stoppered bottles. Into each bottle 0.1 gram of the hydrocarbon was introduced, and after mixing thoroughly with the dry sediment by shaking, the bottles were filled with inoculated sea water. The results of the experiment are summarized in Table IV.

TABLE IV

AMOUNT OF OXYGEN CONSUMED IN 10 DAYS BY BACTERIA IN AGED SEA WATER, PART OF WHICH HAD BEEN TREATED WITH DIFFERENT PETROLEUM HYDROCARBONS, WITH AND WITHOUT ADDITION OF IGNITED MARINE SEDIMENT

Hydrocarbon	*Treatment*	*Initial Dissolved Oxygen Content (Mgm./l.)*	*Dissolved Oxygen after 10 Days (Mgm./l.)*	*Oxygen Consumed in 10 Days (Mgm./l.)*
None (control)	None	6.83	6.51	0.32
None (control)	Sediment	6.65	6.13	0.52
Kerosene	None	6.78	2.34	4.44
Kerosene	Sediment	6.70	0.00	6.70
Gasoline	None	6.84	5.29	1.55
Gasoline	Sediment	6.74	0.03	6.71
Benzene	None	6.82	6.36	0.46
Benzene	Sediment	6.71	1.94	4.97
Crude oil	None	6.87	4.56	2.31
Crude oil	Sediment	6.74	0.00	6.74

It may be observed that with each hydrocarbon tested apppreciably more oxygen was consumed by bacteria when the bottles were partly filled with ignited sediment. Since the sediment itself was not oxidizable as shown by the controls

to which no hydrocarbon was added, it is concluded that the more rapid utilization of the hydrocarbons is due to their greater availability to bacteria on the surface of the particles of sediment on which the hydrocarbons are adsorbed. Söhngen (1913b) noted that silica or iron oxide stimulated the oxidation of petroleum by *Mycobacterium album*, *Mycobacterium rubrum*, and *Micrococcus paraffinae*. Greig-Smith (1914) found that coating kieselguhr with paraffine accelerated its utilization by *Bacillus prodigiosus* and soil bacteria.

Crude oil is oxidized much more rapidly when mixed with marine mud than in sea water, which is partly attributable to the greater dispersion of the oil in mud and its more intimate contact with bacteria. As much as one gram of Kern County crude oil is quantitatively oxidized in 40 days at 22°C. when mixed with 100 grams of marine mud in a thin layer under aerobic conditions. The bacterial oxidizability of other samples of crude oil is being investigated in different kinds of sedimentary materials and simulated environments. Tauson and Shapiro (1934) found that 45 per cent of Emba crude oil introduced into cultures of bacteria isolated from oil wells was oxidized in seven months and the reaction was still continuing.

TEMPERATURE REQUIREMENTS

Most of the experimental work has been conducted at 22°C., although there are some hydrocarbon-oxidizing bacteria which are active at temperatures as low as 0°C., and others are active at temperatures as high as 55°C. No attempt has been made to grow hydrocarbon-oxidizing bacteria at higher or at lower temperatures. Most of the bacteria isolated from the sea will grow at 0° to 4°C. but very few of them tolerate temperatures exceeding 30°C. (ZoBell and Conn, 1940). This is not surprising when one considers that they have come from an environment having a temperature ranging from 3° to 20°C. There must be other places in nature to find hydrocarbon-oxidizing bacteria which tolerate higher temperatures than those which occur in the sea.

Those bacteria which will tolerate the higher temperatures are much more active than at lower temperatures. For example, seven times as much paraffine wax was oxidized at 55° by a given culture as at 22°C. Although there are relatively few species of marine bacteria which grow at temperatures as high as 55°C., according to Morrison and Tanner (1922), bacteria are quite widely distributed elsewhere in nature which grow at temperatures ranging from 45° to 85°C.

SALINITY REQUIREMENTS

Sea water having a salinity of about 3.4 per cent has been used for the cultivation of the hydrocarbon-oxidizing bacteria. Some of the marine bacteria continue to grow even when sea water is diluted as much as 1:10 with distilled water, and most of the hydrocarbon-oxidizing bacteria isolated from the soil grow in very dilute salt solutions. Although only a small percentage of the bacteria isolated from terrestrial or fresh-water sources are able to grow in sea water (ZoBell, 1941), species of *Mycobacterium*, *Pseudomonas*, *Proactinomyces*, and other

microörganisms isolated (by Haas) from mid-continental soil, fresh-water wells, sedimentation ponds in oil fields, and "water bottoms" of petroleum-storage tanks have the ability to utilize hydrocarbons in sea-water media.

Marine hydrocarbon-oxidizing bacteria are active in sea water to which 12 to 15 per cent sodium chloride has been added. This represents a four- to five-fold increase in the sodium chloride content of the sea water, sodium chloride being the principal constituent of sea salt. Similar increases in some of the other constituents are not tolerated as well, and it is still unknown if the bacteria are functional in concentrated brines. Studies on the specific salinity requirements of hydrocarbon-oxidizing bacteria are in progress.

The optimum pH for the activity of hydrocarbon-oxidizing bacteria is between 7.5 and 8.0, but they continue to grow until the medium becomes as acid as pH 6.0 or as alkaline as pH 10.

OXIDATION PRODUCTS

Little is known concerning the intermediate and end products resulting from the bacterial oxidation of petroleum hydrocarbons under different conditions. We have noted acid production, the formation of carbon dioxide and, in some cases, methane from the oxidation of paraffine oil and higher petroleum hydrocarbons in sea-water media. The lowered pH may be due to carbonic acid from carbon dioxide. Johnson *et al.* (1942) report that the ratio of carbon dioxide produced to oxygen consumed ranges from 0.47 to 0.63, according to the hydrocarbon undergoing oxidation. This is in agreement with the findings of Stone and co-workers (1942) who give a mean value of 0.65 for the bacterial dissimilation of light oils. They suggest that organic acids may result from the fermentation of hydrocarbons but give no specific information on this point. Hopkins and Chibnall (1932) report that the intermediate products of metabolism of *Aspergillus versicolor* oxidizing higher paraffines are probably ketones or polyketones, and that further oxidation results in the production of shorter fatty acids.

Haas (1942) found no appreciable quantities of intermediate products resulting from the microbial oxidation of petroleum hydrocarbons although in one experiment a substance behaving like isopropyl alcohol was detected. He interprets the CO_2:O_2 ratio as indicating that hydrocarbons are more or less completely oxidized to carbon dioxide and water. However, he did find evidence that small amounts of oil-soluble acids were formed. Besides traces of acetic acid and lactic acid, Thaysen (1940) noted the formation of methane, acetaldehyde, and ethane from the bacterial decomposition of kerosene. Hydrogen as well as methane production has also been reported (anonymous, 1938) from the bacterial decomposition of kerosene. Most of the 17 species of hydrocarbon-oxidizing bacteria studied by Söhngen (1913a) produced organic acids as intermediate products.

In a series of experiments designed to test the quantitative assimilation of hydrocarbons, the writers introduced enough n-hexane in glass-stoppered bottles of aged sea water with ignited marine sediment to give 2.0 mgm./l. The oxygen

content and the bacterial populations of pairs of bottles were determined after different periods of incubation at 22°C. The bacterial population reached a maximum on the fifth day and oxidation appeared to be complete between the fifth and the tenth day. At this time it was found that after subtracting values for the controls, the hexane had accounted for the consumption of 5.16 mgm. of oxygen. Since the complete oxidation of 2 mgm. of hexane to carbon dioxide and water would require 7.26 mgm. of oxygen, at first thought this might be taken to indicate that only 71 per cent of the hexane was utilized. However, direct microscopic counts showed that 14.3×10^9 bacterial cells were formed per liter. Estimating these cells to contain an average of 25×10^{-12} mgm. of carbon each, it follows that 0.36 mgm., or 22 per cent, of the carbon of the hexane was converted into bacterial protoplasm. Similar results have been obtained with tetratriacontane.

DISCUSSION

It is apparent that microörganisms capable of oxidizing petroleum hydrocarbons are rather widespread in sea water and marine sediments as well as on the land. Though not dependent upon hydrocarbons for their multiplication, hydrocarbon-oxidizing bacteria are generally most abundant in oil- or gas-soaked soils. Whereas ordinary soil may contain only a few hundred hydrocarbon-oxidizing bacteria per gram, Haas (1942) has analyzed crude-oil-soaked soil from Texas, Louisiana, and Kansas which contained from a million to 49 million such bacteria per gram. Similarly Baldwin (1922), Tauson (1929), Johnson *et al.* (1942), and others have noted that oil- or gas-soaked soil or water which has been in contact with oil, such as sedimentation ponds or the water bottoms of oil-storage tanks, is the best place to look for hydrocarbon-oxidizing bacteria.

Since, as might be expected, hydrocarbon-oxidizing bacteria are most abundant around oil deposits, the large number of such bacteria found in some samples of marine sediments may indicate the presence of petroleum hydrocarbons. This possibility is being investigated. A method of prospecting for subterranean petroleum deposits has been proposed by Blau (1942) in which oxidation products formed in the surface soil by hydrocarbon-oxidizing bacteria are detected colorimetrically. The method presupposes that volatile hydrocarbons escaping from oil pools are oxidized by soil bacteria in the presence of atmospheric oxygen. Harper (1939) found increased bacterial populations around leaking natural-gas mains. Similar observations were made by Schollenberg (1930). Sanderson's (1942) method of geomicrobiological prospecting is based upon the ability of certain bacteria to utilize volatile hydrocarbons escaping from subterranean deposits.

According to the literature reviewed by Seyer (1933) and Chibnall *et al.* (1934), heptane, pentadecane, hexadecane, eicosane, heneicosane, docosane, tricosane, pentacosane, hexacosane, heptacosane, octacosane, nonacosane, triacontane, pentratriacontane, and other hydrocarbons occur naturally in certain

plants and insects which have been examined. In view of the widespread occurrence of petroleum hydrocarbons in the waxes produced by plants, Dean Whitmore at Pennsylvania State College proposed that it may *not be a question of how hydrocarbons are formed but rather a question of what has happened to all of the hydrocarbons which have been produced by plants throughout the geological ages.* Perhaps the hydrocarbons have been destroyed by microörganisms in all except certain environments where conditions are not suitable to the activity of hydrocarbon-oxidizing bacteria. Conditions inimical to the activity of such bacteria may be prerequisite to the accumulation of petroleum hydrocarbons in recent sediments. McCoy and Keyte (1934) and others recognize that hydrocarbon-oxidizing bacteria might destroy or prevent the accumulation of crude oil.

Preliminary observations reported in the foregoing pages suggest that in the absence of free oxygen or in the presence of hydrogen sulphide certain hydrocarbon-oxidizing bacteria may not be active. The demonstrated toxicity of sulphide may be of special significance in light of the belief of many geologists that the richest deposition of source material takes place in euxinic muds which are foul with hydrogen sulphide. Crude oil itself is commonly rich in hydrogen sulphide. Besides hydrogen sulphide and low oxidation-reduction potentials, there may be other influences in certain places on the sea floor such as the presence of carbon monoxide, certain heavy metals or other oxidase inhibitors which protect petroleum hydrocarbons from bacterial oxidation. It would be in such environments where one might expect to find hydrocarbons accumulating.

The activity of hydrocarbon-oxidizing microörganisms may help to explain why Trask (1932) and others have failed to find petroleum hydrocarbons in recent sediments. Even if hydrocarbons were in the sediments *in situ*, they might be destroyed rapidly by the increased bacterial activity and altered environmental conditions which accompany the collection and storage of sediment samples. ZoBell (1938) has shown that following the collection of marine muds, the bacterial population may increase tenfold in a few days when stored at 0° to 4°C., and at higher storage temperatures the increased bacterial activity is proportionately greater. Moreover, if the samples are exposed to air or oxygenated water, there are marked changes in the oxidation-reduction potential, hydrogen sulphide content and other properties of the mud.

Methane was the only hydrocarbon found by Thayer (1931) from the fermentation of fatty acids by mixed cultures of bacteria in marine mud, river mud, sea water, and tapwater. Though the writers have no reason to believe that higher hydrocarbons were produced from fatty acids in Thayer's experiments, it is conceivable some might have been produced and then destroyed by hydrocarbon-oxidizing bacteria, although Thayer (1936) recognizes that certain bacteria utilize hydrocarbons. Be this as it may, it is now apparent that the activities of such bacteria must be taken into account when examining either field or experimental material for petroleum hydrocarbons. In the analysis of 17,400 lbs. of gas resulting from the anaerobic decomposition of sewage sludge Rawn, Banta, and

Pomeroy (1939) detected the presence of 0.04 per cent ethane, 0.01 per cent propane and butane, 0.07 per cent pentane and higher hydrocarbons and 0.001 per cent butadiene along with 67 per cent methane, 32 per cent carbon dioxide, 0.03 per cent carbon monoxide, 0.02 per cent hydrogen and 0.004 per cent hydrogen sulphide.

The observations of Thaysen (1940) and Haas (1942) suggest that bacteria which utilize hydrocarbons might be instrumental in causing undesirable changes in petroleum products stored over water. Thaysen isolated bacteria from the water under kerosene- and gasoline-storage tanks, which decomposed these petroleum products with the formation of methane and possibly ethane. When combined with air these gases could form explosive mixtures which might account for "spontaneous" oil fires. An anonymous (1938) report ascribes the explosion of a kerosene tank to the production of methane and hydrogen by the bacterial decomposition of kerosene in the storage water. The theory is advanced in the report that the bacteria obtained their oxygen from sulphate because sulphate-reducing bacteria were found in the storage water.

Haas (1942) speculates that the discoloration of refinery products and sometimes the formation of gummy substances might be attributable to the activity of hydrocarbon-oxidizing bacteria. He points out that the activity of such bacteria also accounts for the deterioration of paraffine-coated underground cables and for the rapid disappearance of petroleum products which pollute fields and waterways.

CONCLUSIONS

Bacteria are widely distributed in sea water and marine mud which are able to oxidize crude oil, petroleum-refinery products, and many pure hydrocarbons. Several species of bacteria representing five or more genera are endowed with this ability. The hydrocarbon-oxidizing bacteria grow best in the presence of free oxygen, but some of them may be able to obtain their oxygen requirements from nitrate, sulphate or other compounds. Hydrogen sulphide inhibits the activity of aerobic bacteria.

Petroleum hydrocarbons are oxidized more rapidly when dispersed on the surfaces of sand grains, asbestos fibers, diatomaceous earth, or other inert particulate materials. When mixed with 100 grams of marine sediment, as much as one gram of crude oil might be destroyed in 40 days at 22°C. The bacteria grow best at temperatures ranging from 20° to 30°C., although some of them oxidize hydrocarbons at temperatures as low as 0° or as high as 55°C. They grow throughout a wide range of salinity and from pH 6.0 to 10.

All of the bacteria produce carbon dioxide and bacterial protoplasm when they utilize hydrocarbons. Methane, organic acids, ketones, aldehydes, and alcohols have been reported as intermediate products.

It is believed that the presence of large numbers of hydrocarbon-oxidizing bacteria in marine sediments may indicate the presence of proto-petroleum.

However, petroleum hydrocarbons probably will not accumulate in detectable quantities in environments where conditions are favorable for the activity of the bacteria. The failure of various workers to find petroleum hydrocarbons in recent sediments may be due to the increased activity of hydrocarbon-oxidizing bacteria following the collection, transportation, and storage of the samples.

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REGIONAL METAMORPHISM OF COAL IN SOUTHEASTERN WEST VIRGINIA[1]

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ABSTRACT

The general geology and stratigraphy of the coal field of southeastern West Virginia are discussed. The regional change in the rank (fixed-carbon content) of the Sewell and No. 3 Pocahontas coal beds is used to measure the regional metamorphism of the coal field. The various theories that have been proposed to account for such regional metamorphism are reviewed critically and their applicability to southeastern West Virginia is discussed. David White's theory of regional metamorphism of coal by tangential pressure is challenged and the validity of his sub-theory of relief of stress by overthrusting questioned. It is concluded that the regional variations in the rank of the coal beds in southeastern West Virginia is due to variations in the maximum depth of burial of those coal beds (load metamorphism).

The present study indicates that if the carbon-ratio theory is valid it must apply both horizontally and vertically (with stratigraphic depth). Reeves has pointed out valid objections to applying the theory in vertical section and the present writer suggests that the theory may be based on insufficient evidence and (or) coincidence. A critical review of the theory is recommended.

INTRODUCTION

While completing a detailed geologic report on Greenbrier County (46) the writer noticed that the fixed-carbon content of the Sewell coal *decreased* from west to east toward the more intensely folded region. Believing that this change in rank was in conformity with David White's theory of relief of stress by overthrusting, material was assembled from the surrounding area for a short contribution to the literature on the subject. When it was found that the percentage of fixed carbon continued to increase gradually westward for more than 25 miles it was decided that the relief of stress by overthrusting was not a satisfactory explanation.

As previously reported by the writer (23) there is a close parallelism between the relative depth to which the Sewell coal has been buried in the different areas and the amount of fixed carbon in this coal in those areas.

It is the purpose of this paper to discuss the regional change in the fixed-carbon content of the coal beds in southeastern West Virginia and to test the applicability of the various theories that have been proposed to account for such regional carbonization of coal beds to the case under discussion. The problem of the origin of the original organic deposits is considered only to the extent that it affects the problem of the regional carbonization of coal.

A special effort is made to use data compiled by other investigators in order to eliminate insofar as possible any charge that the conclusions are based solely on the writer's interpretations and are therefore subject to doubt. The writer wishes to emphasize that all basic stratigraphic data used have been published in reports cited and are therefore available for checking by those that so desire. The isopach maps by R. C. Tucker have not heretofore been published but practically all their basic data have been published in the various County Reports of the West Virginia Geological Survey.

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THEORIES OF COAL CARBONIZATION

The various theories that have been proposed to account for the observed change in the rank of coal from one area to another may be tabulated as follows.

1. Differences in original material
2. Differences in ease of escape of volatile material
3. Differences in age
4. Differences in contact metamorphism or hydrothermal activity
5. Differences in amount of horizontal stress
6. Differences in maximum original overburden

It is not the present purpose to investigate each theory in detail. Some of the theories can not apply to southeastern West Virginia and these are dismissed with brief mention. In other cases only a summary of investigations that seem to prove or disprove a particular theory are given.

1. *Differences in original material.*—In spite of the evidence that has been assembled by White and Thiessen (65, 67, 70, 73), Turner (68), Stadnichenko (59), and others, there are still a few authors who cling to the idea that different ranks of coal are due to different original materials. This theory may be divided into four phases: (a) differences due to variation of climates, (b) differences due to plant evolution, (c) differences due to various parts of plants, and (d) differences in amount of decomposition.

With regard to climatic differences Stadnichenko (59, p. 533) points out that in the Appalachian area the coal changes in rank in an east or west direction while the climate would be expected to change with the latitude. A more comprehensive treatment of the subject is given by White (70, 72).

In the references cited, White and Thiessen show that coals of all ranks are known in Carboniferous, Mesozoic, and Tertiary rocks. In the face of such evidence it is clear that the evolution of plants can not account for the various ranks of coal.

The effects of the various parts of plants upon the analyses of coal have been investigated by White and Thiessen (70), White (73), and Stadnichenko (59) among others.[3] White (71, p. 209, 73, p. 276) has shown that when coals of various types reach the rank of semibituminous (fixed carbon of 70–75), their chemical analyses approach each other and that above this rank the various types have similar or identical chemical analyses. Later Stadnichenko (59, p. 522) showed that, except for fusain, the chemical analyses of the banded constituents of a single coal bed approached each other when the coal reached a fixed-carbon content of 70. The difference between the analyses of fusain and of the bright coal became less and less the higher the rank. Since all of the coals considered in this paper have fixed-carbon contents above 70 it is unnecessary to pursue this phase of the problem further.

The theory that variations in the stage of decomposition of the original organic material (with or without bacteria) recently came to the front again in an

[3] Those interested in this subject should also investigate the U. S. Bureau of Mines publications of Thiessen and Sprunk.

interesting but highly theoretical paper by Fuchs (19). Fuchs purported to show that geologic agencies in general (as they are known in the world's coal fields) could not change the rank of coal. This supposed inability of geologic forces to change the rank of coal coupled with an involved analysis of the probable chemical reactions led Fuchs to the conclusion that bacterial action was the most likely explanation of the carbonization of coal. Apparently recognizing that physical characteristics and rank are ordinarily related, Fuchs suggested that orogenic pressure aided in compaction of coal up to values of 1000 lbs./in.^{2} in the case of bituminous coal and 4000 lbs./in.^{2} in the case of anthracites. No explanation was offered to account for the progressive regional change in the rank of coal, nor did he account for the observed increase in the rank of coal with increase in stratigraphic depth.

McKenzie Taylor has advanced an ingenious scheme for varying the rank of coal by controlling the duration and type of bacterial action. This hypothesis (64) which has received favorable comment in some quarters (14, 18, 19) may be briefly summarized as follows.

1. Bacterial action can account for the carbonization of organic matter to coal. 2. The necessary conditions are an anaerobic environment and some method to control the hydrogen-ion concentration in the material. 3. The roof shales above coals of ranks higher than brown coal have been in contact with saline waters. 4. Base-exchange reactions with the saline water have converted the clay minerals to sodium (or potassium) clays (as opposed to calcium or hydrogen clays). 5. Hydrolysis of these minerals by fresh water has taken place and such hydrolysis has caused the clays to become impermeable and alkaline. 6. Areas in which the roof clays were hydrolized first contain low-rank coals and areas hydrolized last contain high-rank coals.

Many parts of Taylor's work are open to serious challenge but it seems sufficient here to point out that the roof clays (or shales) would not have become relatively impermeable *or alkaline* if the saline water was not replaced by fresh water (step 5, foregoing). In Kanawha, Boone, Roane and other counties of West Virginia saline waters are produced from rocks associated with coal (44) of varying ranks and there is no reason to believe that these coals differ in any way from other coals in the area. There is reason to believe that these saline waters have been in contact with the roof shales of the coals continuously since deposition (25). These coals are certainly not anthracite as demanded by the Taylor hypothesis.

2. *Differences in ease of escape of volatile material.*—A pertinent observation concerning this subject is reported by Holland.[4] The Sewell coal of eastern Fayette County has a volatile content very near the dividing line between low-volatile and high-volatile coal and many sales of the coal depend on a low-volatile classification. Holland reports that experienced mine owners are of the opinion that within a mine where roof conditions vary, the coal with a sandstone roof has a *higher*-volatile content than does coal from under a shale roof. As will be

[4] C. T. Holland, personal communication.

shown, in any vertical section the volatile content of each coal bed is less than that of the coal above. This is the reverse of expected trend if the ease of escape of volatile matter was an important factor.

3. *Differences in age.*—It is known that coals of all ranks occur in Carboniferous, Mesozoic, and Tertiary sediments. It seems, therefore, that the mere lapse of time can at best be only a contributing factor. On the other hand, reports of the formation of firm bituminous coal within less than a geologic period should be viewed with the greatest reserve. Statements that coal of bituminous rank has formed within short periods are generally based on the presence of rounded fragments of coal in coal conglomerates. Stutzer and Noé (63, pp. 156–59) describe secondary allochthonous coal deposits in which peat and brown coals were eroded and redeposited. Their Figure 44 (63, p. 157) shows several well rounded boulders of "brown-coal wood." The writer recently collected a piece of coal conglomerate in Kanawha County, West Virginia, that shows individual flattened coalified plants, small irregularly shaped pieces of coal and well rounded pebbles of coal. The evidence is strong that these pieces that are now coal were in the mature peat or lignite state when they were incorporated in what is now well consolidated sandstone. Most of the pieces of coal show compaction but in some the compaction (though probably present) is not readily observed.

4. *Differences in contact metamorphism or hydrothermal activity.*—This is perhaps the first theory to be proposed to account for the progressive change from high-volatile bituminous coal to anthracite in Pennsylvania (53, pp. 995–97). A few small igneous dikes occur in the coal measures of the Appalachian area but their effect is apparently local (30). As there is no evidence of igneous activity in the coal-bearing rocks of southeastern West Virginia, this theory is not discussed further here. Those interested in such phenomena are referred to the comprehensive descriptions of White (70, 73) and Stutzer (63).

5. *Differences in amount of horizontal (tangential) stress.*—The remarkable general parallelism between the rank of the coal and the amount of deformation of the strata in Pennsylvania was first pointed out by Rogers (53, pp. 995–97). A numbers of years later White and Thiessen (70) showed that the rank of coal generally increased toward the folded areas, and, after citing a number of examples, White proposed that the increase in the rank of coal was caused by thrust pressure developed during mountain building. White discussed his theory in several papers (70, 71, 73, 74) and his views are most concisely stated as follows (70, p. 106).

> Regional thrust pressure, essentially horizontal in direction, acting on and transmitted with diminishing (progressively compensated) force through the buried and loaded coal-bearing strata has converted lignite (brown coal) successively into subbituminous coal, bituminous, semibituminous, semianthracite, anthracite, and even into graphitic coal.

A few years later White wrote (71, p. 198) as follows.

> The effectiveness of thrust pressure as the cause of regional coal alteration is well illustrated in most large areas of high rank coal, but in no part of the world is it more clearly demonstrated than in the great Appalachian coal field.

Anticipating criticism of his theory based on the fact that the fixed carbon of the coals commonly decreases in the vicinity of the deformed areas, White evolved a sub-theory, known as relief of stress by overthrusting (70, pp. 114–25), to account for such anomalies. The failure of some geologists to accept this explanation caused White to make the following statement in his last paper (74, p. 591).

> Emphasizing the dominant importance of pressure in the metamorphism of the organic mother rocks, I stressed particularly the role of competency in assuring greater compressive alteration in competent areas, in contrast to folding or faulting, which compensate or neutralize the thrust. Regions of competency and high carbonization were cited in proof that "disturbance," or folding of the strata, was not a *cause* of the metamorphism but an *effect* by means of which more advanced alteration was averted. Some of my critics have not duly regarded this very important distinction.

It should be noted that White proposed that the thrust pressure was transmitted through the coal measures with diminishing force entirely across the great Appalachian coal field, a distance of more than 150 miles.

In discussing the more fundamental question of earth stresses and earth deformation of the Appalachian area Price (42, p. 42) states:

> It is generally accepted that a mass of heterogeneous sediments will not transmit a tangential stress for any considerable distance.

In a paper dealing specifically with the deformation of the Appalachian plateau (coal) area Sherrill (57, p. 244) states:

> It is generally considered that the tangential stresses which deformed the northern Appalachian region must have been transmitted largely through the Cambro-Ordovician limestones and the Basement Complex. The thick overlying sedimentary section seems entirely incompetent to transmit deforming stresses over the distance involved.

Both Price and Sherrill emphasize the rapid thickening of the rocks toward the east and southeast across the plateau region and both correctly point out that the true center of the geosyncline is on the eastern side of the plateau.

According to Galpin[5] one fact that is well known by most geologists but taken into account by few is that the rocks that are seen at the surface at present in the Appalachian area were deeply buried at the time of deformation. He continues, when rocks fail by folding (Appalachian type) there is every evidence that they behave like plastic material. If this be true it follows that tangential thrust can never develop a stress that is materially higher than the vertical stress. Since the vertical stress is determined only by the weight of the rock column it also follows that the rocks have in every case been subjected to the maximum stress.

Galpin's statement concerning the great amount of material that has been removed from the Appalachian area is in conformity with the work of Lesley (35), Shaw (56), Ashley (2), and Fridley and Nolting (17). His statement with regard to the limit of tangential stress is in conformity with the work of Bailey Willis (79). On the basis of numerous experiments Willis stated (79, p. 274):

[5] S. L. Galpin, personal communication.

Long time, even geologically speaking, is required for the bending of strata. Force, great yet barely sufficient to overcome the enormous resistance, acted through ages gradually to accomplish changes of form, which sudden effort, however mighty, could never have produced. Violence might fracture, crush, destroy; steady pressure alone could systematically bend or shear sedimentary masses.

6. *Differences in maximum original overburden.*—In studying this theory it is possible to obtain direct evidence. If there is any value in the idea it should be possible to demonstrate the existence of the effect by studying the fixed-carbon content of a number of coals in vertical stratigraphic sections. That fixed-carbon content of the coals does increase in the lower coals was apparently first noted by Rogers (53, 54) in 1843. Hilt (28, 29) pointed out the relationship more precisely in 1873 and 1874 and as a result the increase in the rank of coal with stratigraphic depth is often referred to as the "law of Hilt." Hilt recognized that if the rank of coal increased with stratigraphic depth it would also increase in the direction of the thickening of the overlying formations.

In 1879 Lesley (35) proposed that the regional change in the rank of coal in Pennsylvania (including anthracite) was due to the higher-rank coal having been buried more deeply. Lesley pointed out that the coal-bearing formations thickened toward the anthracite region and suggested that the Permian may have been much thicker over the anthracite basin than in the western part of the state. Anticipating the studies of Shaw (56) and Ashley (2), Lesley pointed out that the post-Paleozoic rocks of the coastal area must have come from the Appalachian region. Lesley also pointed out that differences in original overburden could easily explain why "disturbed" Belgian coals are not anthracites and why Arkansas anthracites are not "disturbed."

David White's views on tangential stress as the cause of coal metamorphism have become so widely known that it is usually overlooked that he consistently stated that the coals increased in fixed-carbon content with increase in stratigraphic depth. In the words of White (70, p. 125–26):

> The progressive increase of fixed carbon noted in the successively lower (older) coal beds in passing downward in a normal stratigraphic section was especially pointed out by Hilt in 1873, and is now a well-recognized principle known as the "law of Hilt." The law is, however, subject to very many exceptions, owing to differences in the ingredient debris forming a particular type of coal or to folding and faulting. The former include, for example, coal in which canneloid elements (spores, resins, waxes, etc.) yield volatile combustible matter much greater than that in coal far above them in the vertical section, and disproportionately higher than the coal beneath them.

After citing several examples from various parts of the world White continued (70, p. 127):

> A more extended and systematic inquiry may show the loss to be as high as 0.6 per cent to 100 feet in the [Appalachian] coal field as a whole. This problem invites further investigation.
>
> Before passing from this subject it should be recalled that the loss of volatile matter in vertical direction in passing downward through the coal[-bearing strata] in a thick columnar section is not to be confused with mere depth of cover. The same beds may lose

or gain in volatile matter in dipping beneath the thick cover of other formations according as this dip carries toward or away from the direction of regional increase of fixed carbon. The words in brackets were supplied from other parts of the text.

It should be pointed out here that White specifically denied that variation in cover could cause regional changes in the rank of coal within a single coal bed (73, p. 279).

Numerous studies (3, 20, 41, 60, 63, 67, 69, 70) in various coal fields show that in any local section the fixed-carbon content increases, in bituminous coals, at a rate of 0.5 to 0.8 unit per 100 feet of (stratigraphic) depth. In an outstanding contribution Reeves (48) showed that the fixed carbon increased in the Appalachian area at an average rate of 0.69 unit per 100 feet of (stratigraphic) depth. This value is very close to the rate of 0.6 predicted by White, and Reeves used 0.6 in all of his calculations.

Stressing the point that successively older and older coals come to the surface as the folded areas are approached, Reeves emphasized the fact that only a fraction of the increase in fixed carbon shown on most regional isocarb maps occurs within any one coal bed. Reeves mentioned the probability that regional thickening of overlying formations had induced a regional change in the fixed carbon of a given coal bed (48, p. 804–06) but, in the same paper (p. 799) Reeves largely nullified this suggestion by stating that the coals also increased in fixed carbon with increasing present cover. On the assumption, of course, that analyses of weathered coal are not to be used, there is abundant evidence that variations in present depth of cover have little or no effect upon the fixed-carbon content of the Appalachian coals.

In view of the evidence just cited the writer considers the general increase in fixed carbon with stratigraphic depth in any vertical section to be an established fact. On the other hand, the writer is not aware that it has yet been demonstrated that the regional change in fixed carbon within a single coal bed can be directly correlated with variations in the maximum depth of burial.

GENERAL CONSIDERATIONS

Due to the fact that southeastern West Virginia has been the subject for numerous geological investigations (4, 5, 6, 9, 10, 15, 16, 21, 22, 24, 26, 27, 31, 32, 33, 43, 45, 46, 47, 50, 51, 75, 76, 77), only a brief summary of the general geology is given here. This summary is based on both the literature cited and on personal observations.

Figure 1 shows the approximate per cent of fixed carbon in the coals in the various parts of the state. This figure is largely taken from a similar map of Nolting and Headlee (38) but the isocarb maps of Reger (49), White (73), Eby (10), Thom (67A), and Myers (37) were also considered. Since analyses of samples from more than 70 different coal beds were used in compiling the map it is of qualitative significance only. The entire area considered in this paper lies southeast of the 70-isocarb line and southwest of Pocahontas County.

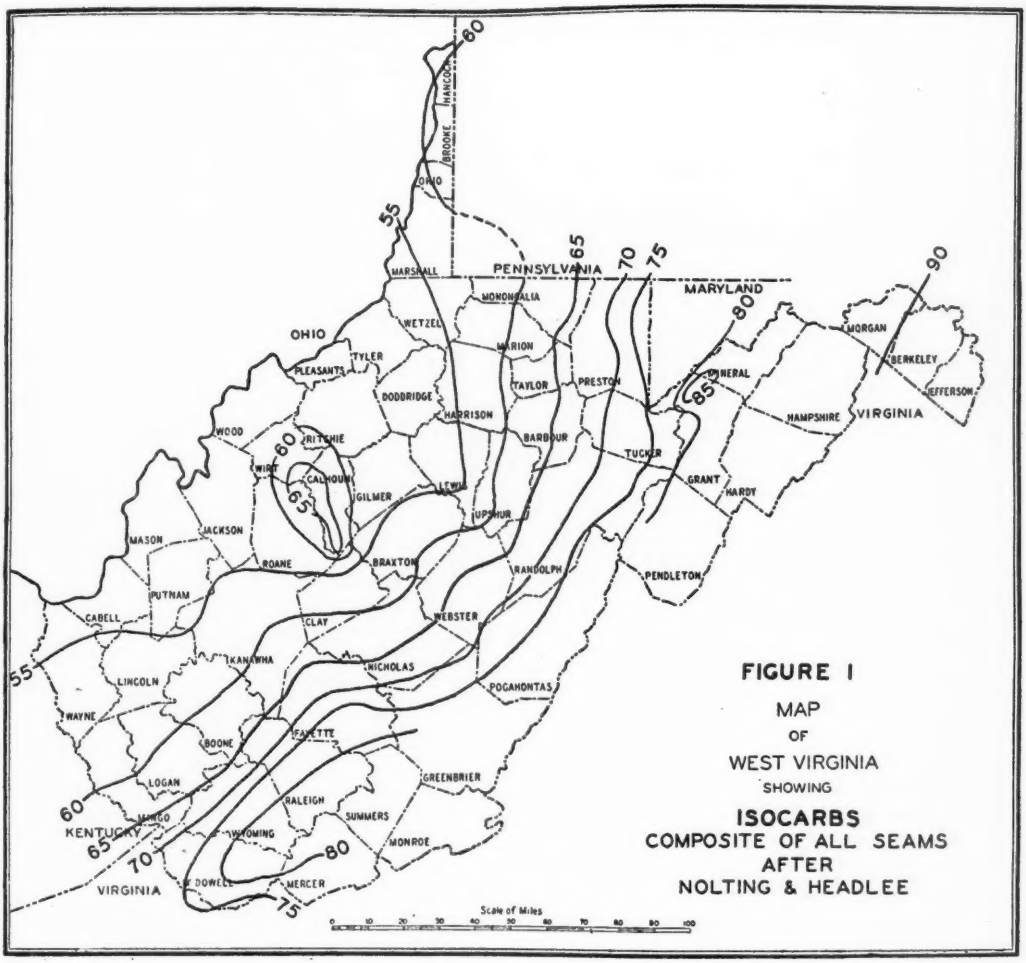


FIGURE 1

MAP
OF
WEST VIRGINIA
SHOWING

ISOCARBS
COMPOSITE OF ALL SEAMS
AFTER
NOLTING & HEADLEE

Figure 2 shows the relative stratigraphic position of all of the known Pennsylvanian and Permian coal beds of West Virginia and their classification by geologic series. Only those coals in the New River and Pocahontas groups of the

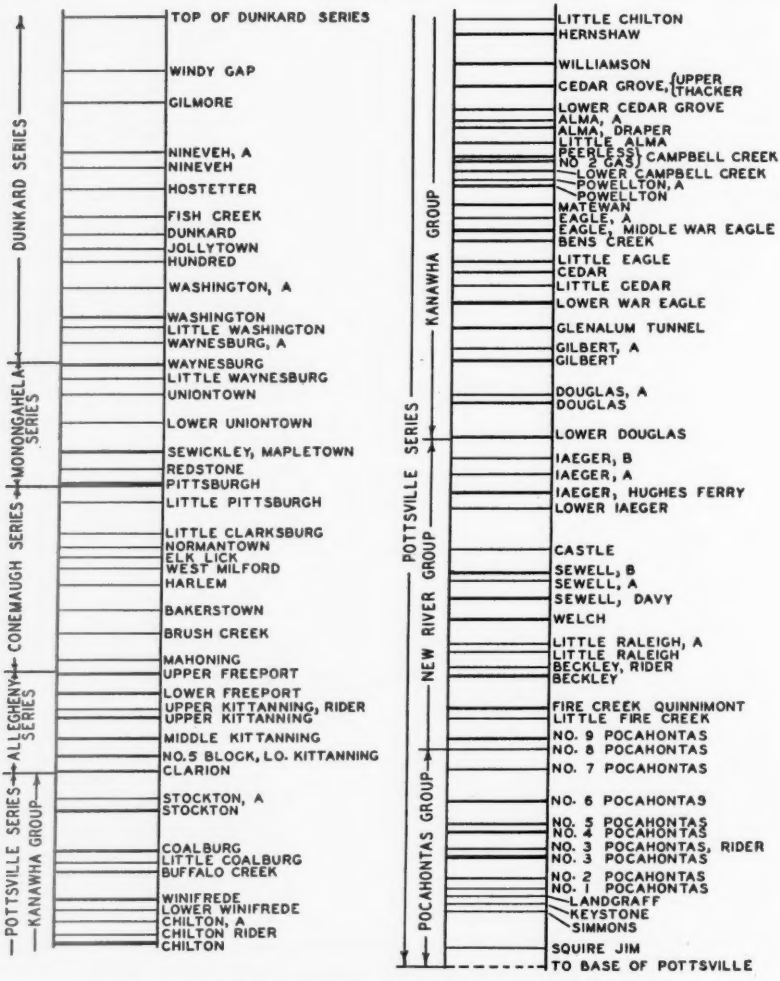


FIGURE 2.—COLUMN SHOWING COAL SEAMS IN WEST VIRGINIA
(AFTER WEST VIRGINIA GEOLOGICAL SURVEY)

Pottsville series crop out in area designated, the formerly overlying beds (Allegheny, Conemaugh, Monongahela, Dunkard, *et cetera*) having been removed by erosion.

No marine fossils have been found in the New River or Pocahontas groups of

the Pottsville but plant fossils are abundant (36). Plants are commonly found in upright position in the roofs and floors of coal mines. These fossils together with the very low ash content of the coals testify to the fact that the coals were formed in place. The same fossils are commonly found embedded in the sandstones and conglomerates, indicating that plant life was abundant throughout Pottsville time in southeastern West Virginia.

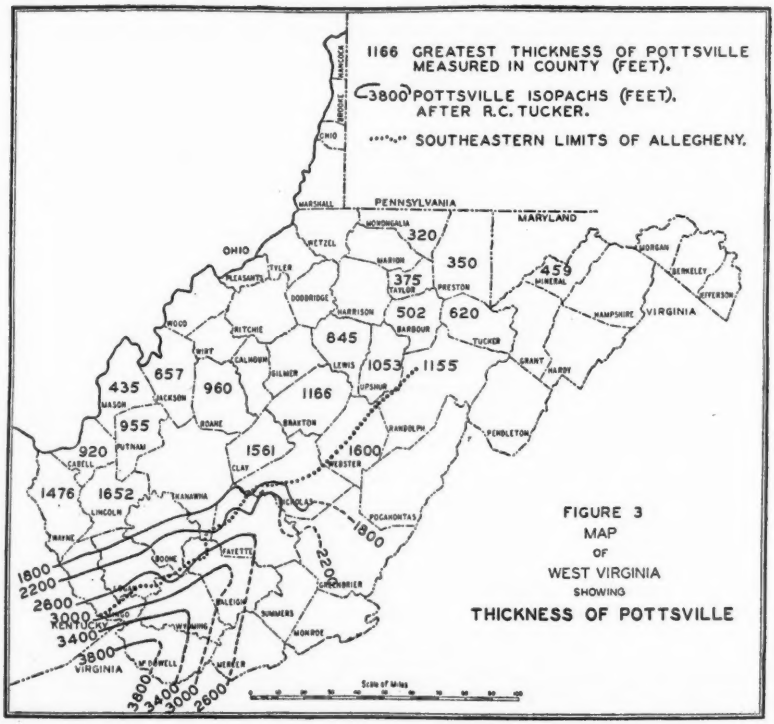


FIGURE 3
MAP
OF
WEST VIRGINIA
SHOWING
THICKNESS OF POTTSVILLE

Figure 3 shows the thickness of the Pottsville series in southeastern West Virginia. The isopachs (equal-thickness lines) are taken from an unpublished map by R. C. Tucker, drawn in June, 1932, and the figures showing the greatest measured thickness of Pottsville in the central and northeastern counties are from Price, Tucker and Haught (45). Also shown on Figure 3 is the southeastern limit of the Allegheny series (top of the Pottsville). Because the top of the Pottsville does not extend over much of the southeastern part of the coal area the isopachs must be viewed as semiquantitative. The thinning of the Pottsville from Wyoming and McDowell counties into Mercer can not be considered as an established fact since the upper part of the series has been eroded. On the other hand, it is entirely possible that Tucker's interpretation of the area is correct.

The regional variations in the total thickness of the Pottsville are due both to the thickening and thinning of the beds as shown by the intervals between coal beds and to the addition or subtraction of beds at the unconformity at the base of the series. This fact is particularly important in studying the cause of the regional variations in the fixed-carbon content of the coals.

There is reason to believe that all of the upper Pennsylvanian and lower Permian rocks, which are now represented only in the northwestern part of the state,

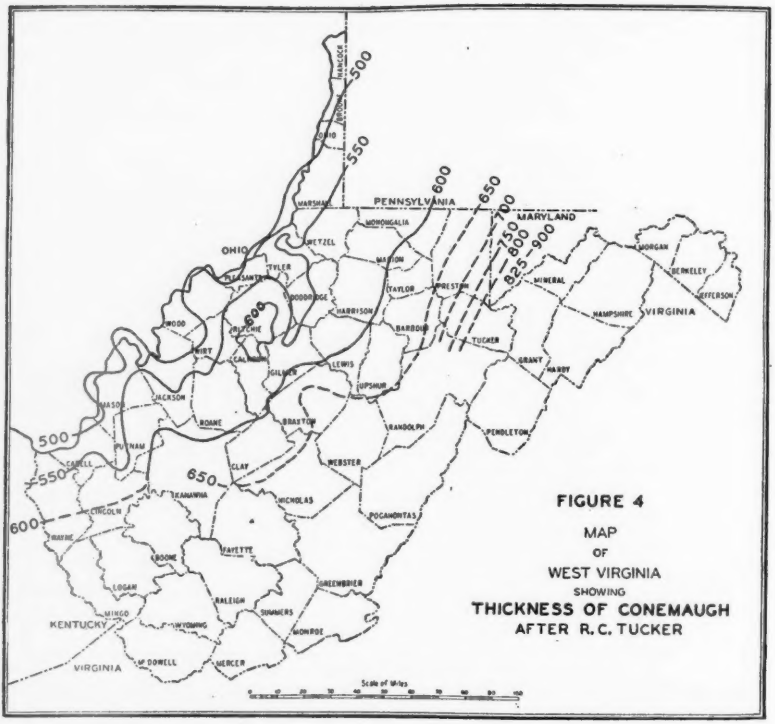


FIGURE 4
MAP
OF
WEST VIRGINIA
SHOWING
THICKNESS OF CONEMAUGH
AFTER R. C. TUCKER

once extended over southeastern West Virginia. As it appears that the fixed-carbon content of the coal is definitely connected with the depth of burial, it is desirable to consider the probable direction of the thickening or thinning of these younger formations.

As an example of the direction of thickening of the younger formations, Figure 4 shows the isopachs drawn on the Conemaugh formation. This figure is taken from an unpublished map by R. C. Tucker which was drawn in April, 1933. From this figure it is seen that the Conemaugh thickens south and east to its last outcrop and this fact makes it virtually certain that the Conemaugh once extended over southeastern West Virginia.

The similarity between the isopachs of Figure 4 and the isocarbs of Figure 1 is striking. An inspection of the original maps shows that if the Conemaugh isopachs are superimposed upon the control points of the isocarb map of Nolting and Headlee (38) the isopach lines will fit the control points used by Nolting and Headlee nearly as well as the lines in Figure 1. The fact that the 550 isopach fits the 55 isocarb, the 600 isopach fits the 60 isocarb, *et cetera*, is obviously a coincidence but in the writer's opinion the parallelism of these lines does indicate a close relationship between the depositional lines and the carbonization of the coal.

The Sewell and No. 3 Pocahontas coals are the most valuable and widespread coals in southeastern West Virginia. As a reflection of the persistency of these beds the structure-contour maps of the various geologic reports on the area are based on these coals. Both coals have sulphur contents below 1 per cent and each coal generally has a very low ash content. The almost total lack of detrital minerals of even silt size in these coals stands in sharp contrast to the coarse sand and conglomerates that occur associated with them. In some places channel fillings of silt and sand are found cutting through the coal beds.

There is evidence that at least some of the smaller lenses of low ash coal in southeastern West Virginia were being deposited at the same time that coarse sands were being deposited near by.

The crowning example of the presence of very coarse detritus with low-ash coal is found in the occurrence of erratic boulders in the Sewell coal of Greenbrier County (43, 46). The erratics vary in size from $\frac{1}{2}$-ounce pebbles to boulders weighing as much as 161 pounds. Some of the erratics occur in bony streaks in the upper part of the coal but most are found in the bottom of the seam. Analyses of channel samples of coal from the mines containing the erratics show ash contents varying from 2 to 5 per cent.

Megascopically the Sewell coal is uniform in appearance throughout its outcrop. It is predominantly a bright coal with a thin layer of dull coal 1–2 feet above the bottom. In the minable area this coal varies from $2\frac{1}{2}$ to 9 feet in thickness, the average being about $3\frac{1}{2}$ feet. Thiessen and Sprunk have made thin-section studies of columns of Sewell coal from mines in Fayette, Raleigh, and Wyoming counties. Table I shows the average petrographic composition of the Sewell coal, in the New River Company's Summerlee mine near the city of Oak

TABLE I

PETROGRAPHIC ANALYSES OF SEWELL COAL (12, p. 10)

Mine	*Type*			*Microscopic Composition*			
	Bright	*Semi-splint*	*Splint*	*Anthra-xylon*	*Translucent Attritus*	*Opaque Attritus*	*Fusain*
Summerlee, Fayette County	81	13	6	44	38	12	6
Cranberry No. 3, Raleigh County	100	—	—	75	20	2	3
Wyoming, Wyoming County	81	15	4	60	23	12	5

Hill, Fayette County, in the New River Company's Cranberry Number 3 mine near Cranberry, Raleigh County, and in the Red Jacket Coal Corporation's Wyoming mine hear Pineville, Wyoming County.

TABLE II

PETROGRAPHIC ANALYSES BY LAYERS (12, p. 10 and 66, p. 13)

Mine	*Layer*	*Thickness of Layer (Inches)*	*Components*			
			Anthraxylon	*Translucent Attritus*	*Opaque Attritus*	*Fusain*
Summerlee, Fayette County	1. Bright	20.2	55	30	7	4
	2. Semisplint	5.2	21	51	24	4
	3. Splint	2.2	8	35	53	4
	4. Bright	11.7	38	48	10	3
Cranberry No. 3, Raleigh County	See text					
Wyoming, Wyoming County	1. Bright	21.6	66	20	7	7
	2. Semisplint	6.6	44	32	22	2
	3. Splint	1.6	13	32	50	5
	4. Bright	13.8	63	23	12	2

Table II gives the petrographic analyses of the individual layers of the Sewell coal in the Summerlee and Wyoming mines. Concerning the sample from the Cranberry No. 3 mine Thiessen and Sprunk report (66, p. 71):

The column of coal received from the Cranberry mine was a clean coal, 37 inches (94 cm) thick, with no partings. No careful petrographic study of this coal was made. Its low-volatile content (approximately 20 percent, moisture- and ash-free basis) and extreme friability combine to make the preparation of thin sections very difficult. Thus the actual percentage of components was not determined; however, from the sections prepared and careful examination of the column itself a brief description of the coal is given.

The Sewell coal from the Cranberry mine is even more friable than that from the Summerlee mine, largely due to its high percentage of anthraxylon (estimated to be about 75 percent), together with its high state of metamorphism. The proportion of translucent attritus was estimated to be about 20 percent. The remaining 5 percent includes opaque attritus and fusain.

The Cranberry mine coal is a uniform bright coal with no splint or semisplint. Both the top and bottom of the column are slightly more anthroxylous than the middle 20 inches. However, this variation probably would have only a slight effect on chemical analyses, agglutinating values or Fischer tests.

The petrographic analyses emphasize the uniform character of the Sewell coal. In the words of Sprunk,[6] "The three columns from the Sewell bed indicate that this coal is predominantly of the bright type and that it is uniform over a wide area."

Table III shows the chemical analyses of channel samples taken at the same points that columns were collected for microscopic study. Table IV gives the chemical analyses of the various layers corresponding with the microscopic analyses given in Table II.

[6] G. C. Sprunk, personal letter dated March 24, 1942.

TABLE III

CHEMICAL ANALYSES OF SEWELL COAL (12, p. 7 and 66, p. 37)

Mine	*As-Received Basis*		*Moisture and Ash-Free Basis*							
	Moisture	*Ash*	*Proximate*		*Ultimate*					*B.T.U.*
			V.M.	*F.C.*	*H*	*C*	*N*	*O*	*S*	
Summerlee	1.9	2.4	27.7	72.3	5.2	88.4	1.7	4.2	.5	15,640
Cranberry No. 3	1.3	2.1	21.5	78.5	4.9	89.9	1.8	2.6	.8	15,730
Wyoming	2.6	3.2	23.4	76.6	5.0	89.8	1.5	3.0	.7	15,670

TABLE IV

CHEMICAL ANALYSES BY LAYERS (12, p. 12 and 66, p. 13)

Mine	*Layer*	*As-Received Basis*		*Moisture and Ash-Free Basis*							
		Moisture	*Ash*	*Proximate*		*Ultimate*					*B.T.U.*
				V.M.	*F.C.*	*H*	*C*	*N*	*O*	*S*	
Summerlee	1. Bright	.7	3.0	26.6	73.4	5.0	88.5	1.6	4.3	0.6	15,520
	2. Semisplint	.8	1.6	26.1	73.9	5.0	88.6	1.7	4.2	0.5	15,520
	3. Splint	.7	9.3	22.6	77.4	4.6	89.0	1.4	4.6	0.4	13,350
	4. Bright	.8	1.3	26.5	73.5	5.1	88.1	1.9	4.4	0.5	15,530
Wyoming	1. Bright	1.0	2.0	23.1	76.9	4.9	89.7	1.6	3.4	0.4	15,650
	2. Semisplint	1.0	2.0	23.0	77.0	4.9	89.9	1.6	3.1	0.5	15,660
	3. Splint	.6	15.6	20.2	79.8	4.6	89.7	1.1	4.3	0.3	15,400
	4. Bright	.9	1.5	23.1	76.9	5.0	89.6	1.7	3.2	0.5	15,640

The percentages of fixed carbon shown in Table III are in agreement with regional change in fixed carbon shown on Figures 5 and 6.

The analyses of the various layers in the Summerlee and Wyoming mines shown in Table IV show that the splint coal has considerably more fixed carbon than does the adjoining bright coal. There is also a difference in the ultimate analyses. These differences are in agreement with the comprehensive study of splint coals made by Sprunk and others (58) but are apparently in conflict with the earlier findings of White (73).

A study of Tables I, II, III, and IV shows that a systematic variation in petrographic components can not be a factor in the regional change in the fixed carbon of the Sewell coal. In the first place, Table I shows that the coals in the Summerlee and Wyoming mines are virtually identical, so far as petrographic analyses are concerned, while Table III shows a difference of 4.3 units of fixed carbon. Secondly, what little variation there is involves a relative increase in the amount of bright coal (or anthraxylon). According to Table IV the bright coal has the lowest fixed carbon and the splint the highest. From Tables I and III it is seen that the Cranberry coal has the highest percentage of bright coal (and anthraxylon) but it also has the highest percentage of fixed carbon in agreement with the regional change in fixed carbon.

Although more variable than the Sewell coal the No. 3 Pocahontas coal is also regarded as a uniform coal. In the minable area herein described the No. 3 Pocahontas coal varies from 3 to 9 feet in thickness and usually has one or two thin partings of bone or shale. Megascopically the coal is predominantly of the bright type. Only one section of the No. 3 Pocahontas coal has been studied microscopically. Table V shows the petrographic analyses of the No. 3 Pocahontas coal in the Buckeye Coal and Coke Company's Buckeye No. 3 mine in Wyoming County near the Raleigh County line. The analyses show the very high percentage of bright coal in the column studied.

TABLE V

PETROGRAPHIC ANALYSES OF NO. 3 POCAHONTAS COAL (13, pp. 10 and 13)

Mine	*Type*			*Microscopic Components*			
	Bright	*Semi-Splint*	*Splint*	*Anthra-zylon*	*Trans-lucent Attritus*	*Opaque Attritus*	*Fusain*
Buckeye	88	2	10	60	20	11	9

TABLE VI

PETROGRAPHIC ANALYSES OF LAYERS IN NO. 3 POCAHONTAS COAL (13, p. 13)

Layer	*Thickness (Inches)*	*Anthra-xylon*	*Translucent Attritus*	*Opaque Attritus*	*Fusain*
2. Bottom high-ash splint	2.4	16	6	22	56
4. Top high-ash splint	1.8	6	44	41	9
1, 3, and 5. Bright coal	36.6	66	20	8	6

TABLE VII

CHEMICAL ANALYSES OF COLUMN SAMPLES AND LAYERS IN NO. 3 POCAHONTAS COAL (13, p. 13)

Sample	*As-Received Basis*		*Moisture and Ash-Free Basis*							
	Moisture	*Ash*	*Proximate*		*Ultimate*					*B T.U.*
			V.M.	*F.C.*	*H*	*C*	*N*	*O*	*S*	
Column sample	2.1	7.5	18.7	81.3	4.6	90.7	1.3	2.8	0.6	15,660
Layer 2. Bottom splint	0.5	26.2	18.1	81.9	4.5	90.6	1.0	3.3	0.6	15,370
Layer 4. Top splint	0.5	10.8	16.3	83.7	4.3	91.5	0.8	2.9	0.5	15,470
Layers 1, 3, and 5. Bright	0.6	4.6	19.3	80.7	4.7	90.9	1.3	2.3	0.8	15,650

Table VI shows the petrographic analyses of the various layers of No. 3 Pocahontas coal in this column and Table VII shows the chemical analyses for the column and layers.

The petrographic analyses seem to fit the megascopic appearance of the No. 3 Pocahontas coal fairly well. In response to an inquiry, however, Sprunk states:[7]

[7] G. C. Sprunk, personal letter dated March 24, 1942.

The only petrographical study of the Pocahontas No. 3 bed made to date is that from the Buckeye No. 3 mine in Wyoming County, which was described in T. P. 684. I believe that this mine should not be considered as typical of the Pocahontas No. 3 bed, and for this reason we should examine columns from other mines, although it may be difficult to do so in the near future.

The ash content of 7.5 per cent shown in Table VII is higher than normal for the No. 3 Pocahontas coal. This high ash content is largely due to the bottom layer of high ash splint coal. It appears likely that this splint layer merges into bone coal in parts of the area and as such it would normally be rejected in sampling and mining.

METHOD OF REPRESENTING REGIONAL METAMORPHISM

In studying the various ranks of coal it would be highly desirable to study the differences in the compounds contained in coal of each rank. Unfortunately the precise determination of even a majority of the compounds in coal has not been possible.

Perhaps the most satisfactory way of expressing the chemical composition of coal is by means of the "ultimate" analysis. In this type of analysis the percentage of carbon, hydrogen, nitrogen, sulphur, and perhaps phosphorus is determined. The difference between the sum of these percentages and 100 is assumed to be oxygen. Strangely enough it is this "oxygen" (which contains all of the uncertainties and errors of the analyses) that seems to be the most significant in analyses of different coals. In addition to the shortcoming just mentioned the determining of the ultimate analysis is time-consuming and as a result it has only recently come into fairly common use.

The type of coal analysis in most common use is that known as the "proximate" analysis. As indicated by its name this type of an analysis is at best only an approximation but the ease of determining the analysis and its general usability has established it as the more or less standard method of evaluating coal. In common with most of the papers on coal metamorphism proximate analyses are used in this study.

In brief, the proximate analysis consists of drying the coal to a constant weight at 105°C. and reporting the loss in weight as "moisture." One gram of ground coal is heated in a platinum crucible in an electric furnace at 950°C. for exactly 7 minutes. The loss in weight minus the weight of the moisture is reported as "volatile matter." Another portion of the ground sample is completely burned and the weight of the residue is reported as "ash." The difference between the sum of the percentage of "moisture," "volatile matter" and "ash," and 100 equals the percentage of "fixed carbon." The analysis is empirical and arbitrary throughout but if the standard methods of the United States Bureau of Mines (61) or of The American Society for Testing Materials (1) are followed the results are generally reproducible by different analysts to within one unit of "fixed carbon."

From the foregoing description it is seen that anything that will affect the loss

in weight upon heating will alter the analyses. Insofar as the variations in "volatile matter" measure the different organic compounds such variations are desirable but Parr (39) has shown that certain inorganic substances commonly present in the ash will also affect the amount of "volatile matter." In the report cited Parr proposed the following formula for calculating the fixed carbon to a "dry, mineral-matter-free" basis.

$$(\text{Fixed carbon} - 0.15\ \text{sulphur}) \times \frac{100}{100 - (\text{moisture} + 1.08\ \text{ash} + 0.55\ \text{sulphur})} = \text{fixed carbon (dry, mineral-matter-free)}$$

In 1935 Fieldner, Selvig, and Fredric (11) proposed a simplified approximation of the foregoing formula as follows.

$$\text{Fixed carbon} \times \frac{100}{100 - (\text{moisture} + 1.1\ \text{ash})} = \text{fixed carbon (dry, mineral-matter-free)}$$

During this investigation the writer has calculated several hundred analyses to the usual "pure-coal" (moisture-and-ash-free) basis and to the moisture, mineral-matter-free basis, using each of the formulas. It seems clear that the moisture-, mineral-matter-free basis is superior to the "pure-coal" basis. For the analyses calculated there appears to be little difference between the more complex formula of Parr and the simplified formula of Fieldner and others. This latter fact is probably due to the very low sulphur content of the coals of southeastern West Virginia (78). Unless otherwise noted the term fixed carbon in this article refers to the moisture-, mineral-matter-free fixed carbon.

Six groups of analyses of the several coal beds were plotted during the course of the investigation: (1) analyses made in commercial laboratories prior to 1913, (2) analyses made in commercial laboratories since 1913, (3) analyses made by the United States Bureau of Mines prior to 1913, (4) analyses made by the United States Bureau of Mines since 1913,[8] (5) analyses made at various times by the West Virginia Geological Survey, (6) analyses of tipple samples, collected and made by the Commercial Testing and Engineering Company for the National Bituminous Coal Producers Board for District No. 7.

All groups of analyses showed that the fixed-carbon content of the coals changed in the same direction, reaching their maximums and minimums in the same areas. Due to changing analytical conditions the various groups of analyses did not show the same amount of fixed carbon for the same areas and it appears that reliable data can not be obtained if any two of the foregoing groups of analyses are combined.[9] For example, analyses made by the Bureau of Mines prior to 1913 failed to check analyses of samples from the same mines made by the Bureau after 1913 by as much as 6 units of fixed carbon. The difference between the groups did not appear to be constant so that it was imperative that each group of analyses be considered separately. Within any one group of analyses two

[8] See *U. S. Bur. Mines Tech. Paper 574*, p. 46 and 590, p. 131, for a discussion of their analyses.

[9] A possible exception to this statement is the combination of groups 4 and 6.

or more samples from the same mine rarely varied more than two units of fixed carbon and a surprisingly large number of them varied less than one unit of fixed carbon.

When considered separately all of the coal beds show a regional change in fixed carbon of approximately the same amount and in the same direction. A preliminary study indicated that while it might be possible to convert the analyses of different seams to a single datum by the use of a factor for stratigraphic difference, such a procedure would introduce many uncertainties, not the least of which would be problems of correlation and the determination of the proper stratigraphic intervals. Fortunately the Sewell coal is sufficiently persistent in minable thickness to be used alone in the northeastern part of the area concerned. Although somewhat less satisfactory, the No. 3 Pocahontas coal is used in the southwestern part of the area discussed in this paper.

Other things being equal it would be preferable to use only the analyses of the United States Bureau of Mines in making studies of the regional metamorphism of coal but it was found that this organization had not collected samples from a sufficient number of mines to give adequate coverage. The analyses of the West Virginia Geological Survey are ideal from the standpoint of coverage but the samples were collected over such a long period of years that it is possible that analyses of different counties are not strictly comparable. Under the direction of the Bituminous Coal Producers Board for District 7 and using A.S.T.M. methods the Commercial Testing and Engineering Company collected and analyzed samples from every commercial mine within a very short period. Even though this latter group of analyses is all of tipple samples it is thought that they are more nearly representative of the coal in the various areas than any other set of analyses available. The writer has checked these tipple analyses against channel samples for several mines and it appears that the fixed-carbon contents (moisture-, mineral-matter-free basis) do not differ by more than 1 or 2 units of fixed carbon.

REGIONAL VARIATIONS IN FIXED-CARBON CONTENT OF SEWELL AND NO. 3 POCAHONTAS COALS

The regional metamorphism of the Sewell and No. 3 Pocahontas coals is shown on Figures 5 and 6. Figure 5 shows the fixed-carbon content of these coals as revealed by numerous analyses of tipple samples from all commercial mines operating in the two beds (analyses of foregoing group 6).[10] Figure 6 is based on the West Virginia Geological Survey analyses of channel samples of prospects and mines (analyses of group 5). So far as the regional change in fixed-carbon content

[10] In this paper it is assumed that all of the mines reported to be mining the Sewell and No. 3 Pocahontas coal beds are actually operating in those beds. A careful check of the correlations, however, indicates that a few of the mines may be mining coals stratigraphically near the Sewell on No. 3 Pocahontas coals but not identical with those beds. The writer is convinced that any errors in detailed correlation that might be present could not be sufficiently large to materially change the regional effects shown on Figures 5 and 6.

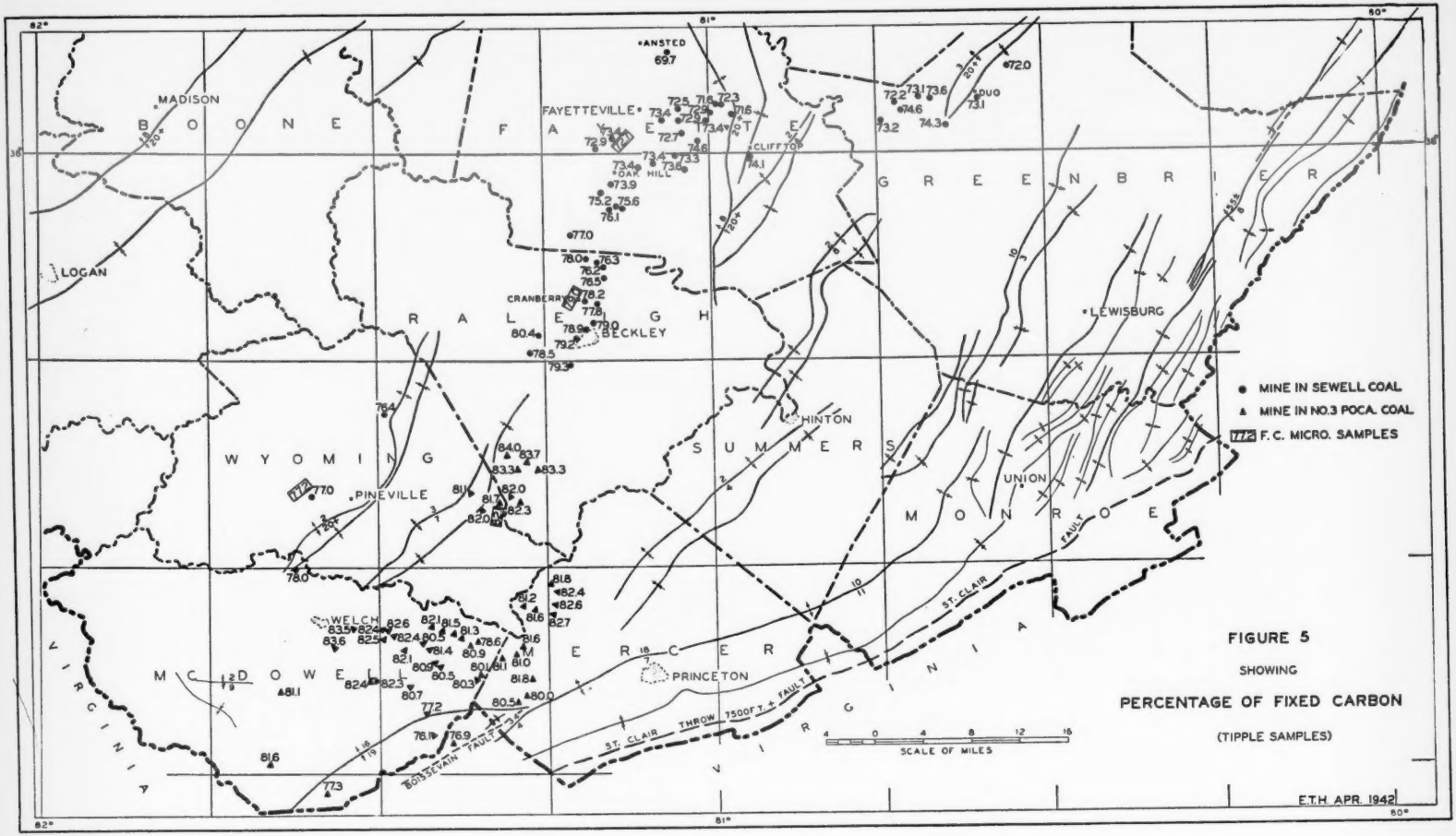


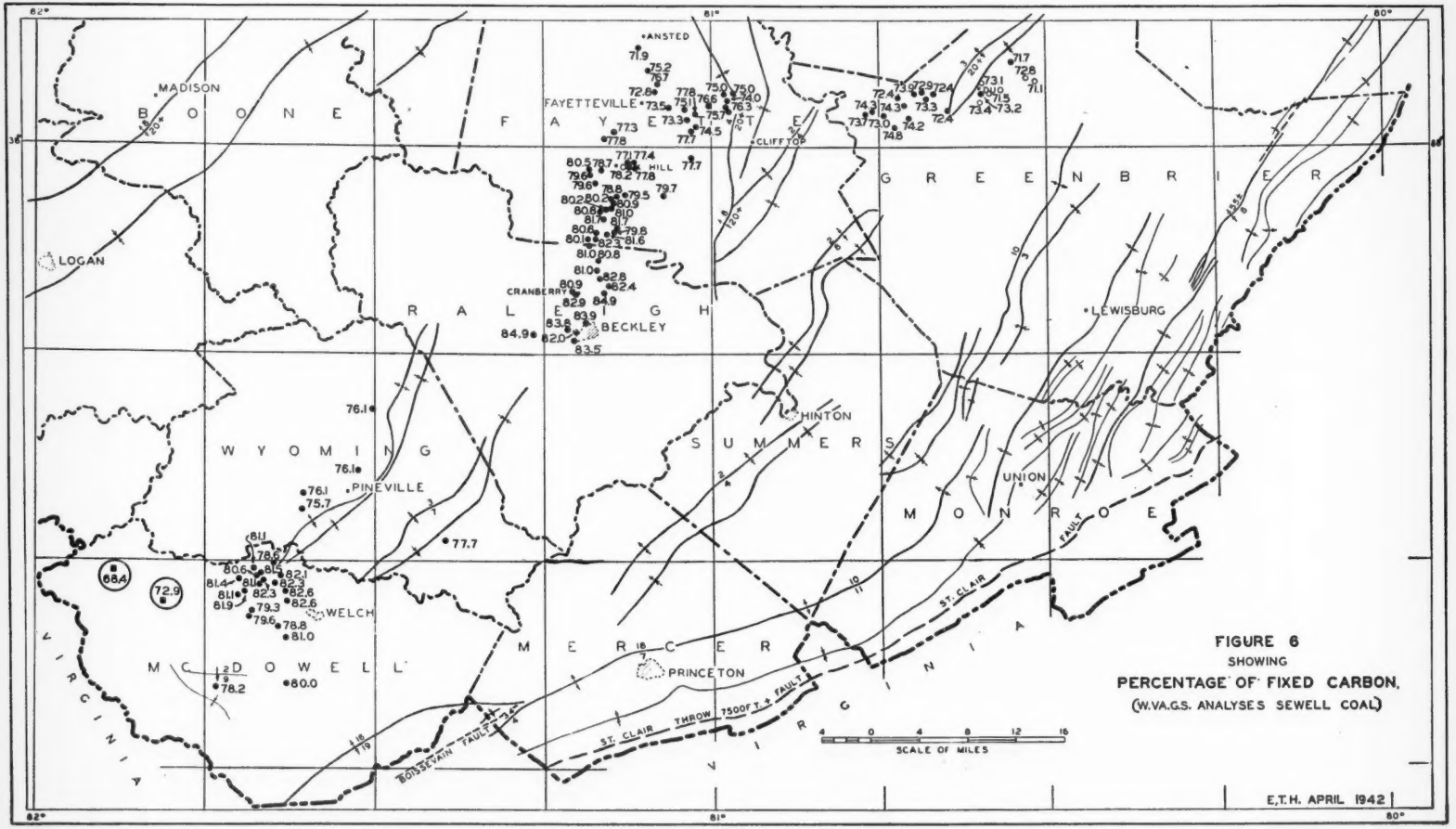
FIGURE 5

SHOWING

PERCENTAGE OF FIXED CARBON

(TIPPLE SAMPLES)

E.T.H. APR. 1942


82°
81°
80°
36°
ANSTED
MADISON
BOONE
FAYETTEVILLE
FAYETTE
CLIFFTOP
GREENBRIER
LOGAN
RALEIGH
CRANBERRY
BECKLEY
LEWISBURG
HILL
WYOMING
PINEVILLE
SUMMERS
HINTON
UNION
MONROE
FAULT
ST. CLAIR
ST. CLAIR THROW 7500FT. ± FAULT
BOISEVAIN FAULT
MERCER
PRINCETON
MCDOWELL
WELCH
VIRGINIA
SCALE OF MILES
FIGURE 6
SHOWING
PERCENTAGE OF FIXED CARBON.
(W.VA.G.S. ANALYSES SEWELL COAL)
E.T.H. APRIL 1942

of the coals is concerned the two figures are nearly the same. Each figure, however, shows some details not shown on the other and for reasons given above the two groups of analyses could not be combined. The fact that the two figures are so nearly alike proves that the regional changes in fixed carbon shown are real and not due to some factor in sampling or analyzing the coal.

Figure 5 shows that the fixed-carbon content of the Sewell coal increases gradually in a westerly direction from 72 near Duo in Greenbrier County to about 77 near the Raleigh-Fayette County line and reaches a maximum of 80 just west of Beckley in Raleigh County. Southwestward from this point the fixed-carbon content of the Sewell bed declines slightly in Wyoming County and increases slightly again in McDowell County. The details of these changes are shown more fully in Figure 6. Detailed examination of the control points in the vicinity of New River in Fayette County shows that the fixed-carbon content of the coal decreases toward the northwest in that area. There seem, however, to be no quantitative data to support David White's statement (74, p. 595).

> The Sewell coal gains 12 per cent of volatile matter in passing westward along New River, and the Helena coal group, in Alabama, increases from 25 to 40 per cent passing from east to west.

The Sewell coal does gain about the amount of volatile matter (100-minus fixed carbon) mentioned by White from a point just west of Beckley, Raleigh County, to Ansted, Fayette County, but the direction of this change is slightly *east of north* instead of "westward."

Figure 5 shows that the fixed-carbon content of the No. 3 Pocahontas coal is lowest near Boissevain, Virginia, and increases northwest, north, and northeast from that point. This regional change in the fixed carbon content of the No. 3 Pocahontas coal has been referred to by White (70, p. 122) and Reeves (48, p. 799) and their explanation of the change is considered in detail later.

As indicated on Figure 1 the fixed-carbon content of the coals decreases toward the southeast in southeastern McDowell County and toward the northwest in the northwestern part of the county. Unfortunately no one coal is present over the entire county so it is not possible to show this effect on one coal bed. The southeastward decrease in fixed carbon is shown by the No. 3 Pocahontas coal as described already. Detailed inspection of the control points on Figure 6 for the Sewell coal west of Welch shows that the fixed-carbon content of this bed decreases slightly in a northwest direction. To emphasize this northwest decrease within individual beds the fixed-carbon content of two analyses of the Douglas coal bed are added (in circles) to Figure 6.

The "hooking back" of the 75 and 80 isocarb lines on Figure 1 is very largely due to the use of analyses from different coal beds. A careful study of the data in southwestern McDowell County and in adjoining Buchanan County, Virginia, showed that there may be a very slight decrease in the fixed-carbon content toward the southwest within individual coal beds but even this slight decrease

was uncertain due to scarcity of analyses and more especially to grave doubts as to the proper correlation of the coal beds.

In Figure 5 the numbers in the small rectangles show the fixed-carbon content[11] of the coal columns that were studied microscopically. It is noteworthy that the percentages of fixed-carbon shown by these analyses of mine samples are practically identical with the percentages shown by the analyses of tipple samples.

CAUSES OF REGIONAL METAMORPHISM IN SOUTHEASTERN WEST VIRGINIA

The foregoing discussion of the various theories that have been suggested to account for the regional metamorphism of coal has restricted the problem so far as southeastern West Virginia is concerned to two possibilities, namely, tangential pressure and variations in the maximum depth of burial.

The surface trace of the crest of all anticlines in southeastern West Virginia is shown on Figures 5, 6, and 8. In order to give some indication of the relative severity of these structures two numbers are shown, one along each side of the anticlinal lines. The number north or northwest of the line gives the height of the anticline to the nearest 100 feet and the number south or southwest of the line gives the distance from syncline to syncline to the nearest mile. In cases where the northwest flank of the anticline merges into the regional dip the width is shown as 20+. The heights of the anticlines were determined from the geologic maps of Price and Heck (46), Hennen (26, 27), Krebs (31, 32), and Reger (50, 51), by using the method devised by Sherrill (57) to eliminate any effects of regional tilting.

If the metamorphism of the coals of southeastern West Virginia is due to tangential pressure it should be possible to relate the amount of fixed carbon in the coals to the structural lines. The largest and most severe anticline within the area in which the Sewell coal crops out is the Mann Mountain anticline in east-central Fayette County. There is no observable reflection of this anticline in the fixed-carbon content of the coal. The systematic variation of the fixed-carbon content of the Sewell coal in Greenbrier County seems to be entirely independent of the well developed structural lines in that area. To be sure the lowest percentage of fixed carbon is shown by the analyses of samples from northern Fayette where the rocks show only a very uniform regional dip (27) but the area west of Beckley which shows the highest percentage of fixed carbon is equally distant from any evidence of folding and shows only the same uniform regional dip (32).

As already described, the fixed-carbon content of the No. 3 Pocahontas coal decreases toward the southeast in McDowell and Mercer counties in spite of the fact that any tangential thrust operating in the area must have operated from southeast to northwest as shown by the overthrust faults and folds, immediately southeast of the coal area. David White has referred to this area as a perfect

[11] Calculated to the moisture-, mineral-matter-free basis from Tables III and IX.

example of his sub-theory of relief of stress by overthrusting (70, p. 122; 73, p. 266). The following quotation from David White (70, p. 122–23) is mainly concerned with the "hooking back" of the isocarbs shown here in Figure 1. White's map (73, p. 257), Thom's map (67A, pp. 86–87), and Eby's map (10, p. 423) show this feature as continuing southwestward several miles into Virginia.

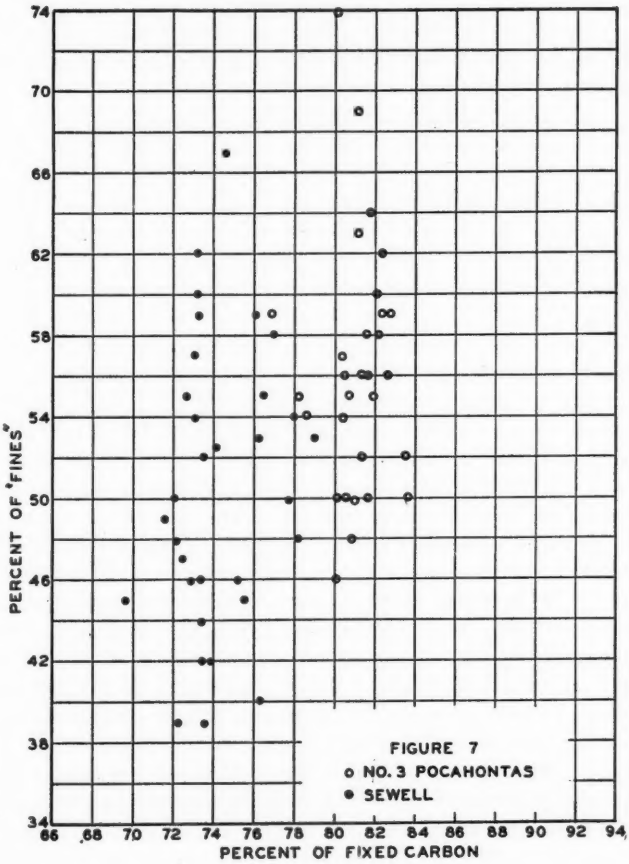
> The greatest reduction, to less than 15 per cent [volatile matter], is found in the region of Widemouth Creek, at the eastern border of the Pocahontas coal field. [Northwestern Mercer Co., W. Va.]
>
> On proceeding farther to the southwestward, following the eastern border of the coal field, again along the strike, from the district of maximum devolatilization, we find a small anticline of rapidly increasing acuteness arising at the border of the coal field. Concomitantly with the development of this fold the volatile matter of the coal (Pocahontas bed) increases nearly to 20 per cent by the time Pocahontas, less than 15 miles from Wenonah, is reached. At the latter point the little anticline is overturned, and there has begun a thrust fault of gradually increasing overlap. The beds behind the fault flatten at once and extend with gentle dips almost horizontally, as in other parts of the field; but as the overlap increases the effects of pressure compensation, particularly in the district lying near behind the dislocation, are immediately seen in a corresponding increase of the volatile matter, so that less than 50 miles farther along the margin of the coal field (along the strike) the volatile matter has increased to about 30 per cent. Before reaching St. Paul, less than 28 miles farther, the thrust has shoved the Cambrian over the edges of the Coal Measures, and the volatile matter of the coal approaches 35 per cent.

Reeves made an extremely effective reply to the foregoing example in his paper criticizing White's carbon-ratio theory. Reeves' criticism follows (48, p. 806).

> He [White] also attributes the decline in carbon ratios southwestward from Pocahontas, in northern Tazewell County, to St. Paul, in eastern Wise County, Virginia, shown by Eby's map, to the compensating effect of an overthrust fault that has its beginning near Pocahontas and gradually increases in amount of overthrust toward St. Paul, and he does not mention the possibility that the decline in carbon ratios in this direction shown by the map may be due to the fact that progressively younger coals are mined in going southwestward along the fault. The Jawbone bed, mined near St. Paul, is 1,600 feet higher in the stratigraphic series than the Pocahontas No. 3 bed, mined at Pocahontas. Coals mined between these two localities occupy intermediate stratigraphic positions. The fact that carbon ratios of the coals in Wise and Lee counties, in southwestern Virginia, are 15 to 17 per cent lower than the coals on the northeast, in southern West Virginia, is also attributed to compensating effects of the great overthrust faults in southwestern Virginia, and apparently no consideration is given to the difference in stratigraphic position of the coals in the two areas. Yet the coals mined in southern West Virginia belong to the Lee formation, and those in Wise and Lee counties to a younger series of coal measures in the Wise formation. The stratigraphic interval between the coals in the two areas ranges from 2,500 to 3,000 feet. When the fact is taken into consideration that the Carboniferous coals show an average increase in carbon ratio of 0.6 per cent per 100 feet in stratigraphic depth, and the proper corrections are made so that the isocarbs indicate the rank of one coal bed, it will be found that the carbon ratio "highs" and "lows" of which Eby speaks disappear.
>
> In the light of the facts set forth it appears evident that in discussions as to the variations in rank of coals in a region, the hypothesis that these are due to differences in in-

tensity of deformation should not be accepted without the consideration of other possible causes, and at least the fact of the variations should be established by a study of individual coals.

As already pointed out under "Regional Variations in Fixed-Carbon Content



of Sewell and No. 3 Pocahontas Coals" the writer has investigated the possibility that individual coal beds decreased in fixed-carbon content southwestward from McDowell County into Virginia. Due to lack of data and doubtful correlations it was not possible to prove that there was absolutely no decrease in fixed carbon but it is certain that the decrease in fixed carbon (increase in volatile matter) within any one coal bed could not even remotely approach the figures given by White.

It has frequently been stated that the friability of coal increases with increasing rank (34, 80). Other things being equal the percentage of fines produced in mining should be a reflection of the degree of friability. The National Bituminous Coal Producers Board for District 7 has collected data on the percentage of coal of various size produced from most of the mines in the area. On Figure 7 the percentage of coal smaller than "nut" size (approximately $\frac{3}{4}$ inch) has been plotted against the percentage of fixed carbon. Of course it must be remembered that the method of mining, shooting, handling, *et cetera*, will exert a very marked influence on the percentage of fines but the total lack of any general trend on Figure 7 would seem to raise some doubt that the percentage of fines is connected with rank.

These same percentage figures have been plotted on Figure 8 to determine whether there is any change that might be related to the structural lines. As might be expected there are several irregularities but there does seem to be a general relationship between the proximity of the mines to the structural axes and the percentage of fines.

That there probably is a relationship between the fixed-carbon content and percentage of fines produced in mining is shown by comparing the percentages in Figures 5 and 8 for western Fayette and Raleigh counties. The structural maps of Hennen (27) and Krebs (32) show that regional dips prevail in these areas and as a result the percentage of fixed carbon and the percentage of fines bear a more or less direct relationship. The fact that Figure 7 shows little or no relationship between the percentage of fixed carbon and the percentage of fines produced in mining is also explained by comparing Figures 5 and 8. The percentage of fixed carbon is about the same in northern Fayette and Greenbrier counties but the percentage of fines is higher in Greenbrier County in response to the more intense deformation. This greater percentage of fines in Greenbrier County is in agreement with the personal observations of the writer and Holland.[12] The fixed-carbon content of the No. 3 Pocahontas coal is similar in Raleigh and McDowell counties but the percentage of fines is greater in Raleigh due to the proximity of the Mullens anticline and syncline. In McDowell County the increasing effect of deformation in the southeast direction has been sufficient to nullify or overcome any effect that the decrease in fixed carbon would have had.

That the percentage of fines does increase with increasing friability is shown by controlled friability tests on coal from two mines in the Sewell coal made by Lawall and Holland (34) and by tests on four mines in the No. 3 Pocahontas coal made by Yancey and others (80). These friability indexes are shown on Figure 8 in rectangles and for convenience the same index figures are tabulated in Table VIII along with the percentage of fines for those mines.

From the foregoing facts it is suggested that the friability of coal may be a combination of three major factors instead of two as is generally supposed. The three factors listed in the order in which their effect would be impressed upon the

[12] C. T. Holland, personal conversation.

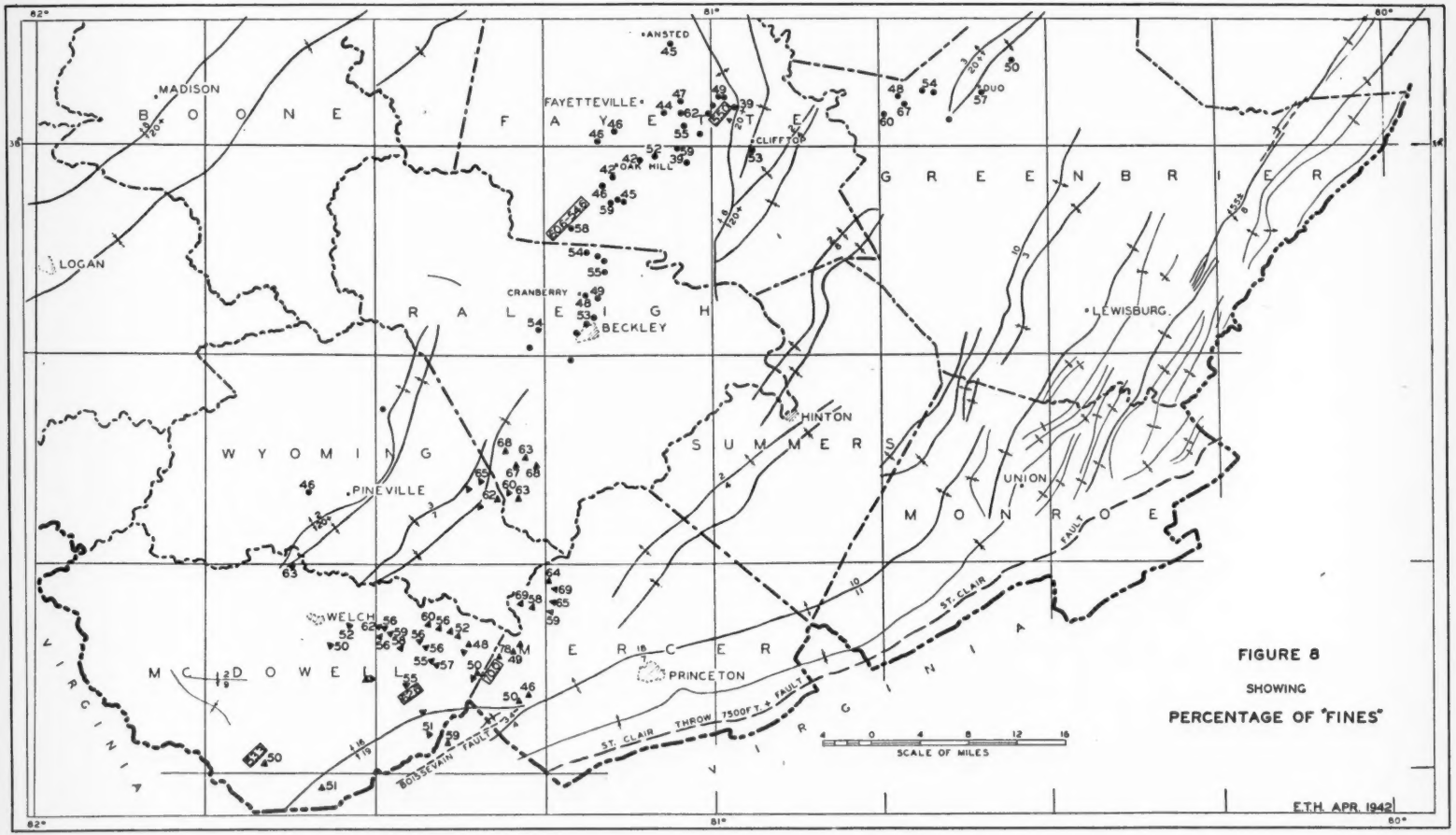


FIGURE 8

SHOWING

PERCENTAGE OF "FINES"

E.T.H. APR. 1942

TABLE VIII

Coal Bed and Reference	*Friability Index*	*Percentage of Fines*
Sewell (34)	55	50±*
No. 3 Poca. (80)	53·3	50
Sewell (34)	54.6	58
Sewell (80) (same mine as last)	60.6	58
No. 3 Poca. (80)	62.6	55
No. 3 Poca. (80)	70.0	78

* Estimated from Figure 8.

coal are: (1) petrographic composition (type of coal, type of banding, partings, *et cetera*), (2) rank of the coal as reflected in the fixed carbon content, and (3) amount of structural deformation.

The total lack of any observable relationship between the fixed-carbon content of the coals of southeastern West Virginia and either the structural lines, the obvious direction of the deforming stress or with the friability of the coal (as reflected by the percentage of fines produced in mining) leads the writer to the conclusion that the regional metamorphism of the coal in southeastern West Virginia is not due to the same tangential forces that caused the major folds in the area.

The agreement between the probable variations in the maximum original thickness of cover and the variations in the fixed-carbon content of the Sewell coal stands in sharp contrast to total lack of evidence that the observed change in rank is due to any other cause.

As shown in Figure 3 the Pottsville series increases in thickness from about 2,000 feet in Greenbrier County to about 3,800 feet in McDowell County. Figure 4 shows that the equal-thickness lines of the Conemaugh probably roughly paralleled the outcrop of the Sewell coal. If it is assumed that the isopachs of the younger formations paralleled those of the Conemaugh, the variations in the thickness of the Pottsville probably show the relative variations in maximum original cover of the coal beds of southeastern West Virginia in a more or less quantitative measure. At first glance, the lack of a marked increase in the fixed-carbon content of the Sewell coal from Raleigh County to McDowell County would seem to discredit any idea that a change in the thickness of maximum original cover accounted for the regional change in rank in that coal bed. However, as pointed out in another part of this paper, the Pottsville formation thickens by both an increase in the thickness of individual beds and by the addition of new beds at the base. The following Table IX shows the total thickness of the Pottsville, the interval from the Sewell coal to the base of the Pottsville, the amount of Pottsville overlying the Sewell coal, the observed fixed-carbon content of the Sewell coal for various parts of southeastern West Virginia, and the calculated amount of fixed carbon necessary to fit the variations in cover quantitatively.

The total thickness of the Pottsville is taken from Figure 3, the interval from the Sewell coal to the base of the Pottsville formation is from bore-hole records and measured sections published in the reports cited, and the observed fixed-

TABLE IX

Locality (See Fig. 4)	*Total Thickness Pottsville*	*Sewell to Base*	*Above Sewell*	*Sewell F. C.*	*Theoretical Value*
A	2,000	650	1,350	73.1	73.1
B	2,300	775	1,525	74.1	74.1
C	3,100	675	2,425	79.2	79.6
D	3,100	750	2,350	76.4	79.1
E	3,200	875	2,325	77.0	79.0
F	3,600	950	2,700	78.0	81.2

carbon contents are from Figure 5. The theoretical value in the last column is calculated by adding 0.6 unit of fixed carbon to the observed value of "A" for each increase of 100 feet of cover.

The close agreement between the observed and calculated fixed carbon requires only the observation that had the present writer indulged in even a slight alteration of the projected part of Figure 3 these figures could have been made identical.

There remains the problem of accounting for the decrease in the fixed-carbon content of the No. 3 Pocahontas coal in a southeastward direction in McDowell County. As mentioned elsewhere in this paper the decrease in the thickness of the Pottsville in this direction shown in Figure 3 can not be considered to be an established fact. That the maximum original cover did decrease in the indicated direction is entirely reasonable however. It has long been recognized that the deposition of sediments in the Appalachian area was ended by a period of folding. It appears probable that the folds that must have preceded the overthrust faults to the southeast of McDowell County prevented the deposition of a full thickness of the youngest beds in the southeastern part of the county. It is even possible that as the fold raised, material eroded from the crest of the fold was deposited in central McDowell County. The very fact that these folds did develop first and were eroded may be one reason why the larger ones are now overthrust faults.

Under the theory of coal metamorphism by tangential stress there seem to be only two possible variables, that is, pressure and the possibility of developing high temperatures by shear. On the other hand, variation in maximum depth of burial certainly involves: (1) increase in pressure with increase in depth, (2) increase in temperature with increase in depth, and (3) increase in amount of dehydration with increase in depth. This third factor is due both to simple squeezing-out of the water by a filter-press action and to a subtraction of water by some process such as evaporation.

The apparent dehydration of the Paleozoic beds in the Appalachian area has provoked much comment and the various theories that have been suggested to account for the phenomenon have been discussed by Heck, Hare, and Hoskins (25, 25A). That this dehydration effect is not due solely to the squeezing-out of water by a filter-press process is shown by the concentration of the connate waters. In general in any given part of West Virginia the concentration of the connate water increases with increase in stratigraphic depth (25).

SIGNIFICANCE OF FOREGOING CONCLUSIONS

If the present conclusion, that the rank of coal is primarily a function of the maximum original thickness of cover, is valid, it follows that the relative thickness of beds now eroded can be determined from the fixed-carbon content of the coals. It also follows that so far as West Virginia is concerned the greatest thicknesses of post-Mississippian beds were in the eastern and southeastern parts of the state.

David White repeatedly stated that the "carbon-ratio theory" applied both horizontally and vertically (with stratigraphic depth). The present study indicates that if the carbon-ratio theory is valid it must apply both vertically and horizontally.

Reeves (48) has shown that when the increase of fixed carbon with stratigraphic depth is considered there is no parallelism between the presence or absence of oil and the fixed-carbon content of the coals in West Virginia. Reeves also pointed out that there has been insufficient drilling to justify condemning areas in which the coals show high fixed-carbon contents (48).

The fact that in West Virginia the percentage of wells that are dry increases as the 65 isocarb line is approached may be explained in two ways: (a) in general, structural conditions are not favorable; (b) as already pointed out the areas of high fixed carbon were also synclinal areas at the close of deposition. Any oil or gas that was generated during or prior to the close of deposition would have migrated as far to the northwest as the permeability of the beds permitted. It does not follow, however, that *all* oil or gas has migrated away from the regions having coals with high fixed-carbon contents.

SUMMARY

The regional change in the fixed-carbon content of the Sewell coal bed in southeastern West Virginia can not be attributed to original or primary differences in the organic material.

There is no evidence that differences in ease of escape of volatile material, age, contact metamorphism, or hydrothermal activity have played any part in the regional change in the fixed-carbon content of the coal beds.

There is no satisfactory correlation between the structural lines or the probable direction of deforming stresses on one hand and the regional variations in the fixed-carbon content of the coal beds on the other.

Load metamorphism (and all that that term implies) probably caused the observed regional changes in the fixed-carbon content of the coal beds.

The carbon-ratio theory (limiting the distribution of petroleum) may be based on lack of information or coincidence. A detailed investigation of the validity of this theory is desirable.

ACKNOWLEDGMENTS

The writer's investigations on the metamorphism of the coal beds in southeastern West Virginia began with his field work while completing a detailed

geologic report on Greenbrier County for the West Virginia Geological Survey in 1935. Since that time the problem has been discussed with numerous individuals and the views of these people have greatly influenced the writer. To all of these individuals the writer expresses his gratitude.

The writer is particularly indebted to S. L. Galpin with whom he has spent many fruitful hours discussing the problems. The kindly criticism of Paul H. Price has added much to the study. The writer is sincerely grateful to Harry M. Fridley for his suggestions and encouragement. The writer also acknowledges his indebtedness to James H. C. Martens without whose guidance and encouragement this study would probably not have been completed. Thanks are due to R. C. Tucker for the use of unpublished material and to Charles E. Hare for aid in preparing the illustrations.

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DISCUSSION

W. T. THOM, JR., Princeton University, Princeton, New Jersey (March 2, 1943).—Dr. Heck has rendered an important service by translating the "law of Hilt" from a rough qualitative generalization into an accurate quantitative statement for one region and probably, by analogy, for most regions, and there seems to be effective justification for his conclusion that former depth of burial is the dominating determinant of the regional variations in carbon ratios which are observable in most coal-field areas. Such a conclusion largely rules out tangential thrust as a major cause of regional carbon-ratio variation, but

I think that we lack evidence to justify a conclusion that tangential thrust (or protection from it) is of *no* significance in causing metamorphism, for the relationships between thrusting and metamorphic change are apparently more indirect and more complicated than was originally suggested. And moreover, since most geologists are chiefly interested in carbon ratios as possible guides to adjacent and subjacent metamorphic conditions bearing on oil occurrence, I think we should plan to make further quantitative studies of all probable causes of low-grade regional metamorphism, in order to reach an effective basis for concluding how far down effective porosity may exist in a region, and how far down oil, and gas, may be present in commercial quantity.

The "load effect," which Dr. Heck points out has been the important one in inducing the metamorphism of the coals in southeastern West Virginia, is after all a compound effect of temperature and pressure. Of these load-pressure seems to be the one chiefly operative in the conversion of the gelatinous colloids of peat into the "hard-rubber" groundmass of lignite, and such "coalification" (which is one form of lithification) apparently has taken place at normal temperatures (50°–70°F.) under the application of pressures of a very few atmospheres. Beyond the coalification point *pressure* seems to be partially effective only as it induces jointing or fracturing of the coal, which provide channels for gases and fluids, and *temperature-effects* quite evidently become the overshadowing causes of coal metamorphism. A temperature rise from 70° to 212°F. will cause the breaking-down of many colloidal coal constituents, with the elimination of "moisture" and methane, and as temperature rise continues, even under identical pressures and depths of burial, the coals affected may move on up in the metamorphic scale to sub-bituminous, bituminous, and anthracitic coals, and possibly even to graphite. The Crested Butte and Anthracite Range regions in Colorado give graphic quantitative illustrations of the facts (a) that systematic regional temperature differences have been the prime causes in systematic regional gradations in coal-metamorphism; and (b) that volatile exudations from solidifying igneous rock-bodies have been the chief heating agents which have caused local temperature rise, and coal alteration.

Dr. Heck's findings are valuable because they give us a significant (and natural) quantitative correlation between present carbon-ratio conditions and past temperature gradients and depths of burial. To complete his picture, however, we still need to learn more about the minimum temperature-pressure-reagent conditions which can convert sandstones into quartzites; about the conditions productive of the evaporative actions testified to by the presence of dry sands, coated with salts derived from connate waters; and about any conditions which may favor either the natural cracking, or the natural polymerization of oils. Dr. Heck has taken us a long step forward toward the use of metamorphic criteria as guides to possible oil occurrence, and I hope that his study of coal-metamorphism may be supplemented by similar quantitative (and regional) studies of lithification and dehydration and incipient metamorphism.

E. T. HECK (March 20, 1943).—I am certainly pleased that Dr. Thom has found my paper acceptable in all major points. The chief purpose of this reply is to "second the motion" so to speak.

As pointed out by Dr. Thom, we need to know more about "conditions which convert sandstones into quartzites." Few if any of the post-Cambrian sandstones in the Appalachian area show distortion of the detrital shape of the sand grains. They qualify as quartzites only because they are so firmly cemented that when fractured they break through instead of around the sand grains. Recent survey work on well cuttings and cores indicates that such quartzitic sandstones may occur at relatively shallow depths in areas that are unaffected by folding.

Observers noted long ago that the Clinton sand became quartzitic downdip from, and southeast of, the Clinton production in Ohio. The change was so marked that predictions

were made that petroleum would not be found at a depth of more than 5,000 feet. The reason given was that metamorphism had destroyed the porosity. Years later a well (J. W. Heinzman's No. 4053) drilled in Roane County, West Virginia, found water in the Clinton at a depth of 7,135 feet and a few miles farther south gas has been found in this formation at a depth of about 6,000 feet. These wells are all more than *50 miles* farther southeast than the older investigations had indicated that porosity could remain.

The quartzitic nature of the Oriskany sand in parts of the great Elk-Poca-Sandyville field has been ascribed to metamorphism and yet this formation shows no more evidence of metamorphism along the structural front than it does in the productive area.

I also agree with Dr. Thom that we need to know more "about any conditions which may favor either the natural cracking or the natural polymerization of oils." David White's generalization that the oils of the West Virginia area become lighter in color and gravity toward the southeast appears to be more or less correct but it does not necessarily follow that this change is due to metamorphism. Neither does it necessarily follow that there must be a "dead line" or "extinction zone" southeast of which oil can not exist.

To the best of my knowledge, no one has demonstrated the presence of petroleum coke in any of the oil or gas reservoirs of West Virginia. As pointed out by Headlee[1] it is difficult to understand how metamorphism could cause the changes in the oil that White noted without the formation of large quantities of coke.

In short, I am aware of no compelling reasons why petroleum may not exist in commercial quantities in the folded Appalachians.

A well[2] has recently been drilled just east of the West Virginia state line in the heart of the folded Appalachians (a few miles east of the line between Hardy and Pendleton counties; see Fig. 1). Drilling was stopped after reaching a depth of 2,986 feet (steel-line measurement), about 2 feet into "pay" (Oriskany sandstone). Krebs reports,[3] "I was not permitted to blow the well, but did get an accurate rock pressure with the exception of numerous leaks around the shutting-in outfit. The pressure in the Oriskany was 1,150 lbs., and in addition to this, there was a 400-pound pressure on the bradenhead gas, which was supposedly encountered at a depth of approximately 1,300 feet.

"I was informed . . . that the open flow was between 75,000 and 100,000 cu. ft. . . . surface elevation 1,460 (barometer)."

The significant features of this well are: (a) the location, which is 70 miles east of present productive limits; (b) the stratigraphic location of the gas and the seemingly orthodox pressure indicates that the accumulation is not due to open fractures and this in turn indicates the presence of porosity; (c) existing carbon-ratio maps indicate a ratio in excess of 80 (see Fig. 1); (d) all gas has not been dissipated in some manner as advocated by proponents of the carbon-ratio theory; and (e) there appears to be no reason to consider this case as an exception.

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[1] Personal communication, March 18, 1943.

[2] Paul H. Price, "Discovery of Gas in Rockingham County, Virginia," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26 (1942), p. 275.

[3] C. G. Krebs, personal letter dated September 13, 1941.

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PROBLEM OF PRE-TRINITY DEPOSITS IN SOUTH TEXAS[1]

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ABSTRACT

Probability of Permian deposits in the East Texas basin is suggested. Attention is directed to the new section of Jurassic, Neocomian, and Trinity deposits in the region of East Texas, Louisiana, and Arkansas, arranged by the Shreveport Geological Society and Ralph W. Imlay, with new names for some of the formations; and the presence of Jurassic deposits in Limestone County, Texas, on the west side of the basin.

Evidence is presented of the progressive increase in basinward slopes on the basement and dips on the sedimentary beds, westward across Arkansas and East Texas, thence southwestward to the locality of San Antonio, thence continuing westward to the Rio Grande. For this 700 miles of generally uniform trend it is postulated that the slopes and dips are functions of sediment load. In general, the greater slopes and dips are toward localities of greater loads of sediments within the basin. The conclusion is that, at comparable locations with reference to the shore, the pre-Trinity deposits in South Texas are thicker than in East Texas, Louisiana, and Arkansas.

Some criteria are suggested for locating the Jurassic shore line. Importance for possible oil and gas production along the continental shore, and the shores of peninsulas and islands, is stressed. Probability of the presence of undiscovered salt domes in South Texas is pointed out.

It seems probable that large areas of the Gulf Coastal Plain are underlain by deposits of Permian age. Undoubtedly that region was a basin in Permian time as it was later, in Mesozoic time. Not far north and west of this basin were regions of high topography. The Bend arch region was flooded by the early Permian sea, which continued eastward across the Strawn basin at least as far as the Texas equivalent of the Choctaw fault. A little later, the region of the Texas Permian basin began to subside, the Bend arch was uplifted and 3,600 feet thickness of Upper Pennsylvanian and early Permian sediments were eroded from that structure.

The part of that débris that went down the western drainage is present to-day in the Permian basin of West Texas. A somewhat equivalent amount must have been carried eastward. If in that direction the Texas equivalent of the Ouachita Mountains was a barrier, then those mountains must have afforded a comparable quantity of material that was carried eastward into the basin.

Farther north was the complex of old "highs" collectively known as the Red River uplift, which was extensively eroded during Permian time. That uplift continued southeastward with increasing elevations and breadth into eastern Denton County, where it seems to have been buried by overthrust blocks of Ouachita relationships. Sediments apparently derived from the uplift during Permian time lie in the West Texas basin, and on the north in the Frederick syncline in Oklahoma. The material eroded from its east end, or from the thrust blocks that covered it, must have gone eastward into the East Texas basin. Still farther north and east, during most of Permian time, were the Wichita and the Arbuckle mountains in Oklahoma. They are surrounded by Permian sediments,

[1] Manuscript received, February 4, 1943.

[2] Independent geologist.

2,200 feet thick as measured 3 miles north of the Healdton field in the Ardmore syncline, in T. 3 S., R. 3 W., Carter County, Oklahoma. The Permian sediments are 2,400 feet thick in the Sherman-Marietta syncline in T. 5 S., R. 3 W., which is the southwest township of Carter County.[3]

The Permian is at the surface in the Ardmore syncline as far southeast as Hoxbar, in the southeast corner of Carter County, and about 10 miles from Red River at the north point of Cooke County, Texas, beyond which it is overlapped by the Trinity sands.[4]

Measured along the axis of the syncline, Hoxbar is about 30 miles from the point where the syncline crosses the Choctaw fault, in which 30 miles the syncline plunges southeastward all the way, and the evidence indicates that the drainage has been in that direction since Middle Permian time or earlier. Until the contrary is learned, the inference is that the Permian clastics continue below the Trinity sands all the way into the East Texas basin.

The question next arises why, if these inferences are correct, Permian sediments have never been reported from the East Texas basin. There are two possible explanations. First, around most of the margin of the basin, where the line is reached where pre-Trinity deposits occur, the lower part of the sedimentary section has faulted down beyond the depth to which any drilling has been done. Where that critical line is crossed, all the drilling thus far done has disclosed a thick section of older Mesozoic rocks that has not been completely penetrated. We do not know what lies below them. Second, it is possible that Permian beds may have been drilled at places and were not recognized as such.

In Grayson County, Texas, there are about 500 feet of pre-Trinity red shales, red sands, and red conglomerates that probably would be considered Permian in age if they had been encountered a few miles farther north, on the opposite side of Red River. That section occurs in the Peter Oil and Gas Company's Jackson No. 1, two miles south of Denison; the McCarty Oil Company *et al.* J. A. O'Dell No. 1, 1,800 feet south of the Jackson well; and in the deep city well at Sherman, Texas, drilled by B. J. Harper in 1921.

PRE-TRINITY MESOZOIC HORIZONS

In introducing this topic the point of departure is certain conclusions presented in papers already in the literature, beginning with W. C. Spooner's "Oil and Gas Geology of the Gulf Coastal Plain in Arkansas,"[5] the work done by the Shreveport Geological Society, particularly a paper by Roy T. Hazzard,[6] Ralph

[3] George E. Burton, "Relation of the Base of the Red Beds to the Oil Pools in a Portion of Southern Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 2 (March–April, 1921), p. 173; Fig. 1, p. 174.

[4] Sidney Powers, "Crinerville Oil Field, Carter County, Oklahoma," *Structure of Typical American Oil Fields*, Vol. 1 (Amer. Assoc. Petrol. Geol., 1929), pp. 192–210; Fig. 1, p. 194.

[5] W. C. Spooner, *Arkansas Geol. Survey Bull. 2* (1935), pp. 20, 32, 33.

[6] Roy T. Hazzard, "Notes on the Comanche and Pre-Comanche Formations of the Ark-La-Tex Area; and Suggested Correlation with Northern Mexico," *Guide Book of Shreveport Geological Society 14th Annual Field Trip* (1939), pp. 155–78.

W. Imlay,[7] and shorter references from other sources which will be credited where used.

Spooner recognized the presence of pre-Trinity sediments in Arkansas and Louisiana. He believed that all of them that had been penetrated at the time his paper was written were Cretaceous in age, and he referred all of them to the Neocomian. In descending order these included the "Lower Marine," later termed the Cotton Valley formation, the Buckner formation and the Smackover limestone. At the time of his writing, rock salt had been found in the Smackover field but he made no attempt to assign the salt to any definite age.

On the basis of ammonites recovered from wells, which were identified by Gayle Scott, W. S. Adkins, and Ralph W. Imlay, and other fossils compared by Imlay with forms found by him and his associate workers in northeastern Mexico, this pre-Trinity section has been subdivided by the Shreveport Geological Society and Imlay as shown in Figure 1.

One of the more striking features of this new section is the correlation of the lowest member of the lower Glen Rose, the Sligo formation, with the Travis Peak formation at its type locality in western Travis County, Texas, and with the Cuchillo formation of northern Mexico. This correlation was made on the basis of short-range ammonites common to the three formations. The section of clastics, ranging up to 2,000 feet in thickness, formerly considered as the Travis Peak, is now assigned to the Neocomian and is named Hosston. All below the Hosston is Upper Jurassic in age, according to Imlay, with some dissenting opinions as to the ages of the Buckner and the Cotton Valley formations, which some would retain in the Neocomian. The Smackover limestone and the Eagle Mills formation, the latter consisting of redbeds, anhydrite, and salt, are referred to the Jurassic apparently by common assent.

Of still greater interest, the Cotton Valley and the Buckner formations were recognized in a well on the western side of the East Texas basin, the Stanolind Oil and Gas Company's Norris No. 1 in southern Limestone County, and it seems to be generally agreed that the Smackover limestone and the Eagle Mills formation, the latter containing nearly 800 feet of salt, also are present in the Norris well. The Cotton Valley formation was recognized in a second well in Limestone County, the Pure Oil Company's Kendrick No. 16, about 3 miles west of Mexia. Furthermore, the last 82 feet drilled in this well before its abandonment at the total depth of 8,847 feet was a dolomitic limestone which probably is Smackover in age.

Because of the discovery of Jurassic deposits on the west side of the basin it becomes a matter of great importance to learn, if we can, how extensive these older formations are on that side of the basin, and whether or not they are geographically continuous with the contemporaneous formations in northern Mexico, on the one hand, and with those in East Texas, Arkansas, and Louisiana, on the

[7] *Arkansas Geol. Survey Inform. Cir. 12.*

TABLE I. RECENT CHANGES IN AGE-REFERMENT AND IN NOMENCLATURE in the Trinity and older deposits of East Texas, Louisiana and Arkansas. After Shreveport Geological Society and Ralph W. Imlay.

		FORMER NOMENCLATURE	PRESENT NOMENCLATURE
LOWER CRETACEOUS	Trinity division	Paluxy formation	Paluxy formation 270′ - 1,600′
		Upper Glen Rose	Mooringsport formation 75′ - 750′
		Massive anhydrite	Ferry Lake anhydrite to 500′
		Lower Glen Rose	Rodessa formation to 500′
			Pine Island formation 280′ - 500′
			Sligo formation * 160′ - 300′
	Neocomian	Travis Peak	Hosston formation 1,600′ - 2,300′
UPPER JURASSIC Oxfordian to Tithonian inclusive		Lower Marine	Cotton Valley formation 2,275′ - 3,175′
			Buckner formation 275′ - 495′
			Smackover formation 900′ - 1,200′
			Eagle Mills formation 450′ - 1,200′
			Morehouse formation to 1,200′

* Travis Peak in age.

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FIG. 1

other. This seems to be important from an economic standpoint, because several formations in these older beds are producing large quantities of oil in East Texas, Louisiana, and Arkansas. Possibly they will produce oil elsewhere also.

Figure 2 is a sketch map of the southern part of the United States, Mexico, and Cuba. On the basis of papers by numerous geologists, a heavy line inscribes the locations of known Jurassic rocks within this area. It will be noted that these deposits occur on the Yucatan peninsula, and in the states of Tabasco, Vera

FIG. 2.—Numbers indicate locations at, or near, which Jurassic, or presumably Jurassic, deposits occur.

1 Altair, Sonora
2 On Rio Hermosillo, near town of same name, Sonora
3 Malone Mountains, Texas
4 Guadalupe, Chihuahua
5 Cuchillo Parado, Chihuahua
6 San Pedro, Durango
7 Jimulco, Durango and Coahuila
8 Southwest and west of Monclova, Coahuila
9 Ohio Mexican Oil Company's Zambrano No. 1, Coahuila
10 Mexican Gulf Oil Company's San Ambrosio No. 1
11 City of Saltillo, Coahuila
12 City of Monterrey, Nuevo Leon
13 Conception del Oro, Zacatecas
14 San Carlos Mountains, Tamaulipas
15 Northern oil fields, Tamaulipas
16. San Luis Potosi, State of same name
17. Southern oil fields, Vera Cruz
18. Stanolind Oil and Gas Company's Norris No. 1, Limestone County, Texas
19. Palangana and Piedras Pintas salt domes, Duval County, Texas
20. Markham salt dome, Matagorda County, Texas

Cruz, and Tamaulipas, Mexico, where they are near the shore of the Gulf of Mexico. They are present in the San Carlos Mountains of northern Tamaulipas, only about 100 miles from Brownsville, Texas.

But they extend inland also. The Upper Jurassic and Neocomian deposits occur south of and on both sides of the ancient Coahuila peninsula. On its western

side they extend northward across the Rio Grande into Texas and far westward into the state of Chihuahua. With ever closer relationships to conditions prevailing in the Gulf Coastal Plain of Texas, Jurassic deposits occur in the San Marcos valley and at Menchaca of east-central Coahuila. These localities are about 125 miles west of Laredo, Texas. But Jurassic fossils have been found nearer Texas than that. Imlay,[8] on the basis of a paper by Carlos Burckhardt and F. K. Mullerried, cited by him, reports that in black carbonaceous limestones from the Mexican Gulf Oil Company's San Ambrosio well an ammonite, *Kossmatia*, and many bivalves were found. This well is near Cameron and only about 30 miles west of Laredo, Texas. This *Kossmatia* is said to have a range restricted to the Portlandian.

In the Ohio Mexican Oil Company's Zambrano No. 1, in northeastern Coahuila, and 18 or 20 miles west of Del Rio, Texas, a thick section of arkose and other beds were found which are believed to be Jurassic in age. The writer does not know that Jurassic fossils were found but he does know that the material is very different from the sub-Cretaceous rocks in the many wells drilled a short distance eastward, on the Texas side of the Rio Grande. He also knows that the Lower Cretaceous at the Zambrano well is considerably thicker than at Del Rio, and it has a different lithologic facies at the base, which is believed to signify older rocks than any occurring on this side of the River, only 20 miles distant. The arkose probably is the equivalent of the arkose farther south in Coahuila, southwest of Monclova, which is Jurassic in age.

Near the Zambrano well is one place where a close approximation can be made of the location of the shore line of the Jurassic sea. It is along the base of the southwest flank of the Del Rio anticline, the core of which consists of marble and schists that are Paleozoic in age. That shore line is in Mexico, and locally approximately parallels the Rio Grande.

Eastward from these Mexico occurrences, nothing is known directly of any Jurassic deposits short of southern Limestone County, Texas, but an attempt will be made later in this paper to develop a strong probability of a connection of Jurassic deposits between these two localities.

If we correlate what appears to be tabular salt in the Stanolind Oil and Gas Company's Norris well, Limestone County, previously referred to, with the intrusive salt of the interior salt domes of the basin, and the salt in these with the Eagle Mills salt, also tabular in the Smackover field, which is Jurassic in age, then we have substantial continuity of Jurassic deposits from Limestone County through Leon, Houston, Freestone, Anderson, Henderson, Smith, Rains, and Wood counties. From the salt domes in this group of counties there is only a few miles gap to the East Texas, Louisiana, and Arkansas region where the presence of the Jurassic is established. Still farther east, in east Louisiana, there is a salt dome in Madison Parish, and at least five others in Mississippi, along this same

[8] "Upper Jurassic Pelecypods from Mexico," *Jour. Paleon.*, Vol. 15, No. 5 (September, 1940), p. 395.

general belt. Pre-Trinity beds, possibly Jurassic in age, are reported in the Union Producing Company's deep well on the Hatchetigbee anticline, Choctaw County, Alabama. Still farther east, Jurassic rocks have been encountered in two deep wells in Marion County, Florida, which is a little north of the center of the peninsula,[9] and their presence has long been known in the west third of the island of Cuba.

We do not know whether the intrusive salt in the coastal salt domes is Jurassic in age or not. Since both Permian and Cretaceous age assignments have their proponents, we may arbitrate the argument by suggesting a mean, which would be Jurassic. That would be the logical inference since it is so close to great masses of salt that are now believed to be of that age.

In Texas it is becoming increasingly difficult to draw a line that will be north of the coastal salt domes and south of the interior salt domes. If we start with the Clay Creek dome in Washington County, which seems always to be mapped with the coastal domes, and compile a table of salt domes in order of their distance from the coast of the Gulf of Mexico, we get something like the following.

Name of Salt Dome	*County*	*Distance in Miles from Coast*
Clay Creek	Washington	118
Ferguson Crossing	Grimes	123
Kittrell	Houston	126
Navarro Crossing (?)	Houston	158
Marquez	Leon	167
Oakwood	Freestone-Leon	169

Oakwood is definitely associated with the salt domes of the Tyler basin. The greatest gap in this table of distances is 41 miles, between Kittrell and Marquez. If the presence of salt at Navarro Crossing should be proved, as some expect it to be, the gap will be reduced to 32 miles and it will be between Navarro Crossing and Kittrell. Until the contrary is proved, the inference seems to be justified that the salt beds in two localities of considerable salt deposition 32 miles apart, or even 41 miles apart, are of approximately the same age. If that inference is correct, then the salt in the domes out under the Gulf of Mexico and that in the Hainesville dome in Wood County, third county from the north line of the state, and the salt in all the domes intervening, are of the same age. If part of it is Jurassic, all of it is Jurassic.

The occurrence of Jurassic sediments in a deep well in Mexico, near Laredo, Texas, has already been mentioned, and there are two known salt domes in Duval County, only 70 miles east of Laredo. A third salt dome, Gyp Hill in Brooks County, is 35 miles south of the other two. East of the Duval County domes no salt has been reported in drilling until the Markham dome in Matagorda County is reached, a distance of almost 170 miles. However, gravity minima occur at many places in this intervening area, and it well may be that enough of these

[9] Robert B. Campbell, "Outline of the Geological History of Peninsular Florida," *Proc. Florida Acad. Science*, Vol. 4 (1939), pp. 94, 95.

minima will be proved to be salt domes to provide substantial continuity of the salt, presumed to be Jurassic in age, across this 170-mile gap.

From Markham eastward there are salt domes all the way, at least to the Mississippi River delta, and northward most of the way across Texas. From Louisiana the salt extends into the southern counties of Arkansas, and in Mississippi apparently as far north as the Tinsley field, near the southeast corner of Arkansas and 250 miles from the Gulf coast.

Thus it appears that the Upper Jurassic sea came in from the south and swept almost completely across the Gulf Coastal Plain from the Yucatan peninsula at least to the Mississippi River delta. In Mexico it reached northward, entirely across that republic and into Hudspeth County, Texas. Farther east it extended northward into Arkansas. The presence of Jurassic sediments in two deep wells north of the center of the Florida peninsula, and on the west third of Cuba raises the probability that the Jurassic sea was connected with the Atlantic Ocean in that locality.

How closely and definitely can we determine where the ultimate coast line was? The belief has already been stated that in Mexico, across from Del Rio, Texas, it may be located with a small error. In Limestone County, Texas, probably it may be located more closely than at the Mexico locality. In the Farrell Drilling Company and Frank Bryan's Gilliam No. 1, drilled in the west part of that county in 1941, metamorphic rocks (Ouachita phase) were encountered at a depth of about 4,867 feet. From the top of the Trinity division to the depth where the well was abandoned is 2,471 feet, which must be approximately the thickness of the Trinity division at that locality.

A strike line drawn northward from the aforementioned Norris well, in the same county, passes 12 or 13 miles east of this well. The Norris well penetrated more than 6,000 feet of sediments and evaporites after topping the Trinity division, and was abandoned without having reached the basement. The difference in the thickness of the pre-Fredericksburg deposits within that 13 miles distance thus exceeds 3,500 feet. The Norris well had about 2,000 feet of Hosston (Neocomian) and about 2,300 feet of Jurassic deposits. The Gilliam well record shows no Jurassic. However, it shows more than 1,100 feet of section that was regarded as Travis Peak although part or all of this may be Hosston.

Here we can draw another segment of the Jurassic coast line, between the Gilliam well and the strike line through the Norris well. This line should be drawn rather close to the Gilliam well, because it seems improbable that Jurassic deposits exceeding 2,300 feet in thickness at the Norris well could have been laid down within very much less distance than 13 miles from the shore.

Almost certainly these deposits end at a fault plane which was a fault scarp of Ouachita phase rocks during their deposition. A well drilled anywhere on the west side of that fault probably will encounter these altered rocks underlying the Comanche, with possibly a part of the upper Hosston which may have overlapped the fault for a short distance and now intervenes between the Comanche and the

altered rocks. A well drilled on the basinward side of the fault probably will not encounter rocks of Ouachita phase at any depth. The basement there must be foreland sedimentaries or igneous rocks of the old Llanorian continent.

A fault in the basement and in the older sediments, along which there is so great displacement, must have definite expression in the younger sediments, even though there is no displacement there. We know that sediments debouching into basins pile up in greater thicknesses close to shore, compared with areas farther out. It seems certain that the relatively greater thicknesses of the Permian and Mesozoic deposits in the shoreward margin of the basin must have loaded and depressed that margin, increasing the displacement along the fault as deposition continued.

Since the beginning of Tertiary time the belts of heaviest loading have progressively moved gulfward, causing a gulfward-moving wave of depression on the basement, and today the area of greatest load is near the present coast line of the Gulf of Mexico.

In the locality of Corpus Christi the basement has been depressed to the extent of 13,000 feet since the beginning of Vicksburg time. That is the thickness of the Vicksburg and post-Vicksburg sediments, all of the deposits indicating that they were laid down at very near sea-level. If sea-level has remained about uniform with reference to the center of the earth during that period, then the basement must have continuously given way under increasing load, maintaining the plane of deposition near sea-level.

In addition to the progressive depression wave moving in the basement toward the Gulf, there has been a gradual gulfward tilting of the entire Coastal Plain area. The hinge line of much of this tilting has been this great subsidence fault that marks the plane between the Ouachita phase rocks on the one side, and the Permian, Jurassic, and the older Neocomian deposits on the other. The result of this basement depression and tilting, the rate of which rapidly increases gulfward and which has carried with it all the sediments resting on it, has caused greatly increased dips, especially in the Washita and older beds, on the gulfward side of the fault, as compared with the dips on the opposite side. A good name for the line where this abrupt increase in the dip rate begins would be the "Basin Margin flexure." In subsurface structure maps it is a striking feature along the upper part of the Coastal Plain, at least across most of Arkansas and all of Texas.

Figure 3 shows profiles of basinward slopes on the basement. The first four are in Arkansas and are adapted from Spooner's Plate III.[10] Profile *A* from Newport to Marion, Arkansas, is the farthest east. Profile *D* is near the west line of the state. It passes through Clark and Nevada counties and through the town of Prescott. Nos. *B* and *C* are intermediate between *A* and *D*, all being about equally spaced. In discussing this feature Spooner, on page 27, says:

> An abrupt change in the rate of inclination of the basement floor along a line drawn

[10] W. C. Spooner, *op. cit.*

from southern Little River County, eastward into east-central Ouachita County, and continued from that point in a northeasterly direction into Cleveland County, is indicated by the records of deep wells. To the north of this line, the basement floor lies at depths

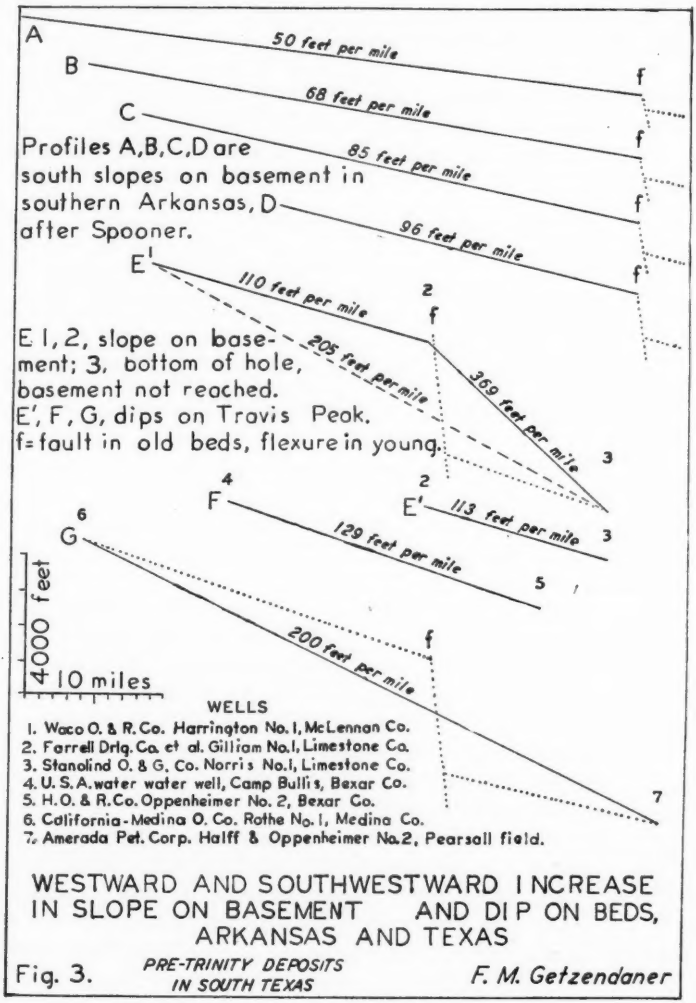
A
50 feet per mile
B
68 feet per mile
C
85 feet per mile
Profiles A,B,C,D are south slopes on basement in southern Arkansas, D after Spooner.
96 feet per mile
E'
110 feet per mile
2
f
E 1, 2, slope on basement; 3, bottom of hole, basement not reached.
205 feet per mile
369 feet per mile
3
E', F, G, dips on Travis Peak.
f=fault in old beds, flexure in young.
4
F
2
E'
113 feet per mile
3
6
G
129 feet per mile
5
4000 feet
10 miles
200 feet per mile
f
7
WELLS
1. Waco O. & R. Co. Harrington No. 1, McLennan Co.
2. Farrell Drlg. Co. et al. Gilliam No. 1, Limestone Co.
3. Stanolind O. & G. Co. Norris No. 1, Limestone Co.
4. U. S. A. water water well, Camp Bullis, Bexar Co.
5. H. O. & R. Co. Oppenheimer No. 2, Bexar Co.
6. California-Medina O. Co. Rothe No. 1, Medina Co.
7. Amerada Pet. Corp. Halff & Oppenheimer No. 2, Pearsall field.
WESTWARD AND SOUTHWESTWARD INCREASE IN SLOPE ON BASEMENT AND DIP ON BEDS, ARKANSAS AND TEXAS

Fig. 3. *PRE-TRINITY DEPOSITS IN SOUTH TEXAS* *F. M. Getzendaner*

ranging from sea level to 2,500 and 3,500 feet below sea level; to the south, wells hundreds of feet deeper failed to reach the base of the Lower Cretaceous. . . .

The abrupt change in the slope of the basement floor may be due in part to the sharp flexing and in part to faulting. . . . The flexure is in large part the result of movement at

the end of the Comanche epoch, but the oldest known Cretaceous sediments (Neocomian?) [now known to be Jurassic] do not extend north of the flexure, and the Travis Peak formation [now the Hosston and Neocomian in age] decreases in thickness over the flexure, suggesting that the initial movement occurred in the earliest Cretaceous [now Jurassic] time. . . . In a general way the flexure coincides with the outlines of the Lower Cretaceous [now in large part Jurassic] basin of deposition.

All the parenthetic phrases in the quotation, excepting the first, are by this writer. Later, on the same page, Spooner makes out a good case for faulting as a cause of the abrupt change in the slope of the basement floor, at least along one line of dip. He says:

The best evidence of faulting along the flexure is afforded by the records of the C. E. Murdock Eagle Mills No. 1 well in sec. 29, T. 12 S., R. 15 W., and the Barnsdall and Foster's Freeman-Smith No. 1 well in sec. 8, T. 13 S., R. 15 W. The distance between these two wells in a north-south direction is less than 4 miles. The Murdock well found quartzitic sandstone, very hard carbonaceous brown shale, and very hard, white non-fossiliferous limestone which are considered to be of Paleozoic age, in contact with the basal Upper Cretaceous sediments. The Barnsdall and Foster well, on the other hand, found typical Trinity red shale and sand in contact with the basal Upper Cretaceous, which continued to the bottom of the hole, a thickness of 500 feet.

It may be noted on profile *A*, the most easterly one, that the rate of slope is 50 feet per mile. That on *B* it is 68 feet per mile. On *C* it is 85 feet per mile, and on *D*, the most westerly one, the rate is 96 feet per mile, showing a progressive increase in the rate of slope as we go westward. None of these lines crosses the flexure mentioned by Spooner.

Insufficient information is available to prepare profiles showing slopes into the north side of the basin in Texas. Profile *E* is from the (1) Waco Oil and Refining Company's Harrington No. 1, north of Waco, in McLennan County, through the (2) Farrell Drilling Company and Frank Bryan's Gilliam No. 1 in western Limestone County, to the (3) Stanolind Oil and Gas Company's Norris No. 1 in southern Limestone County. For the purposes of this cross section the Stanolind well has been moved northward along the line of strike to the line of dip through the other two wells.

On the top of the Ouachita phase rocks we get a slope averaging 110 feet per mile between wells 1 and 2. Between wells 2 and 3 the slope average is 369 feet per mile. Since well 3 did not reach the basement and is used as though it had reached it, and, since probably Permian deposits are present below the depth where the well was abandoned (thus making the interval to the basement a considerable one), it seems probable that complete information would increase the rate of 369 feet per mile slope to a much larger figure. Because this profile crosses the fault and flexure line, the word "slope" is inaccurate. By far the greater part of the change in elevation of the basement is due to faulting in the basement and in the older sediments. It is conditions such as in this profile, and profile *G*, that prove the presence of the fault.

Farther south insufficient information is available to construct profiles on the top of the basement, and the top of the Travis Peak sands has been substituted as the reference horizon in that area. These are the first notable sands below the top of the Glen Rose formation and though their top is not everywhere at the same stratigraphic level, it is the best marker available in the moderately old beds.

Profile *E'* shows the dip of the new horizon between wells 2 and 3 of profile *E*, the same profile we have been discussing. The dip on our new horizon is at the average rate of 113 feet per mile as compared with *more than* 369 feet per mile slope on the basement between the same wells. Of course the slope on the top of the basement everywhere is greater than the dip on any horizon in the overlying sediments, therefore, the change in horizons greatly flattens our profiles. It may be noted, however, that the rates of dip on the new horizon increase rapidly as we go southward and westward around the margin of the Coastal Plain, just as was the case in the slope on the top of the basement.

Profile *F* is 22½ miles long. It extends from the United States Army water well at Camp Bullis in Bexar County, southward through the city of San Antonio, to the Humble Oil and Refining Company's Oppenheimer No. 2, also in Bexar County. The rate of dip on the top of the Travis Peak sands is 129 feet per mile.

The locality of profile *G* is about 55 miles westward along the regional strike from the line of profile *F*. Profile *G* is from the California-Medina Oil Company's Rothe No. 1, in Medina County, southward to the Amerada Petroleum Corporation's Halff and Oppenheimer No. 2 in the Pearsall field in Frio County. The dip is about 200 feet per mile. The Rothe well got the Ouachita phase rocks below only a short run of sand. Those rocks probably do not occur in the Pearsall field and the basement there has not been reached. Probably the deepest wells in the field were abandoned in the Hosston formation.

Profile *G* is comparable with profile *E*. The lines of both cross the fault and flexure. The basin margin flexure passes through the northern parts of Frio and Zavala counties, and probably the Halff and Oppenheimer well is about the same distance into the basin as the Norris well, Limestone County.

The general picture of the Texas end of the long belt that has been discussed is well shown by the belt of brown contours on the Georgetown formation on the *Structural Map of Texas*, by E. H. Sellards, 1939 edition. On the north, the view should be restricted to the area west of the Tyler basin axis. In that locality Sellards found it possible to show by the depths of the Georgetown formation, the dip into the basin for a distance of about 80 miles, from the vicinity of Kennedale, Tarrant County, to a point beyond Canton in Van Zandt County. The average dip rate shown along that line is 68 feet per mile.

From that locality, southward, the brown-colored lines are seen to converge and the belt where it was possible to use the Georgetown for mapping purposes, progressively narrows, until it is only 20 miles wide in western Guadalupe County, where the average dip rate is 175 feet per mile.

Although the flexure line is less conspicuous on the Georgetown than on the Travis Peak sands, it is still discernible. It is weak on this marker at the north, but it is suggested near Farmersville in Collin County, at the town of Rockwall in Rockwall County, at the east corner of McLennan County and near Marlin in Falls County. In the vicinity of Cameron, Milam County, the map shows an abrupt increase in the rate of dips of the Georgetown, from 105 feet per mile, on the west, to 190 feet per mile on the east. At a point north of the Hilbig field in Bastrop County, the change is from 125 feet per mile to 227 feet per mile. At a point north of the Salt Flat field in Caldwell County the increase is from 125 feet per mile to 285 feet per mile. Figure 4 is an adaptation of the part of Sellards' map just discussed.

Along the westward strike of the beds, southwest of San Antonio, through Frio and Zavalla counties, the flexure line is near the south edge of the belt mapped on the Georgetown limestone in that area; therefore, it can not be seen on this structure map. Still farther west, in the vicinity of Del Rio, the large contour interval and the fact that the top of the Georgetown has been removed by erosion over much of that area, resulted in a map picture that is largely opposite the conditions that exist there. The Del Rio anticline does not appear on the map at all.

In summary, the profiles in Figure 3 and the contours in Figure 4 show that there is an ever-increasing rate of slope on the basement, and dips on horizons in the sediments, southwestward and then westward across southern Arkansas; and in Texas, again westward, thence southwestward and once more westward for an over-all distance of more than 700 miles along the margin of the Gulf Coastal Plain. The facts presented and the discussion have shown that throughout this great distance there is a definite line along which these slopes and these dips abruptly increase to a large degree, beyond which line the basement has not been reached in drilling.

Postulate.—In general, in this great regional feature, the displacement at any point along this old subsidence fault is a function of sedimentary load. If the fault is ignored, the rate of basement slope, or the rate of formation dip along any dip line, is a function of sedimentary load. The greater the load basinward, the greater the rate of basement slope and the greater the rate of dip toward the loaded region.

If that postulate is correct, and there is an aggregate of 7,000 feet of Jurassic and Neocomian deposits in northern Louisiana, as stated by Imlay, then in comparable localities in South Texas there must be even greater thicknesses of deposits of those, and possibly older systems.

It is remembered that no generalization relating to conditions in a region as extensive as the one under study is applicable to every part of that region. Some parts of the region have had their own local histories, and doubtless there were great inequalities in the topography of the basement when deposition began.

In the locality of the Uvalde salient, complications enter the picture, and the flexure line is more difficult to follow. The shore line was more involved. There were one or more land promontories with faulted sides during Glen Rose time

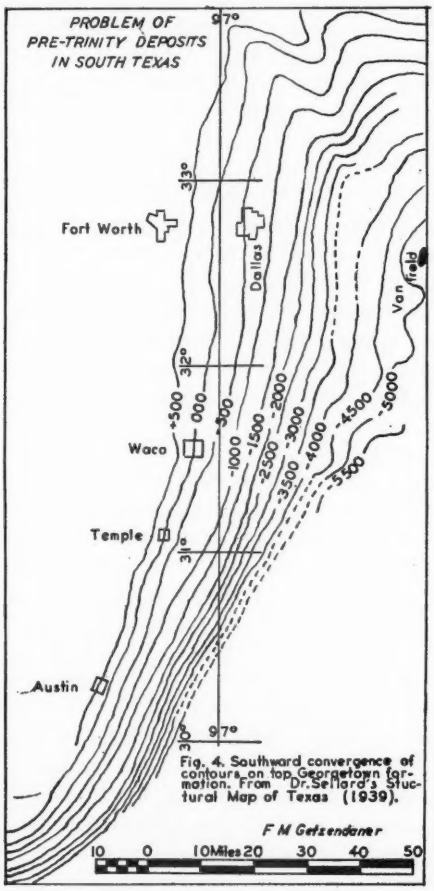

Fig. 4. Southward convergence of contours on top Georgetown formation. From Dr. Sellard's Structural Map of Texas (1939).

with some evidence that they were old even then. However, the line of flexure continues in a generally westerly direction to a locality in southeastern Kinney County. There it is approaching the province of the Chittim anticline, which is believed to be within the Jurassic basin, but which is so large that, on its northeast flank the beds are dipping *toward* the old shore line instead of away from it. Somewhere in that locality the line turns northwestward and passes along the

southwestern side of the Del Rio anticline into Mexico, where its features already have been discussed.

The geological department of the Wellington Oil Company, through Wm. H. Curry, has released to the writer for use in this connection some features of that company's seismograph survey in the vicinity of the Chittim field in Maverick County, 18 miles northeast of Eagle Pass, Texas.

> This reflection seismic work in the vicinity of the gas wells reveals an energy break at the depth of about 14,000 feet. This break affords a good correlatable horizon which gives a picture a little different from the pictures on the other horizons, yet bearing some resemblance to them. It is interesting to note that the structure at 14,000 feet is much more accentuated yet it has no appreciable shift from the structures on the higher beds.

There is no sure means of determining what causes this energy break. One possibility is that it is the basement. Tentatively adopting that hypothesis, let us see whether it fits with the known and reasonably inferred conditions. In some localities it is possible to predict approximately the depth to the base of the Trinity division, the top of the Glen Rose being known, from the known rate of thickening of that division. In this region the southern flank of the Texas Ouachitas, like the corresponding feature in Arkansas, was eroded to a peneplain and the Trinity sea entered a region of low relief. That was the general condition. There are known local exceptions.

The nearest locality where these rates of thickening are known is north of the Chittim field, in Val Verde and Kinney counties. From the Magnolia Petroleum Company's Whitehead No. 1 in northeastern Val Verde County, southward a distance of 46 miles to the same company's Wardlaw No. 1, western Kinney County, the rate of thickening of the Trinity division is 20 feet per mile. From the Phantom Oil Company's Ingram No. 1, in Val Verde County, southeastward to the East Del Rio Oil Company's Weathersby No. 1, in the eastern part of the town of Del Rio, Val Verde County, the rate is 10 feet per mile. The distance is 57 miles.

Eastward in Uvalde County the rates are higher. From the Phantom Oil Company's Cloudt No. 1 in northwestern Uvalde County, southeastward 29 miles to the Humble Oil and Refinining Company's Anderson No. 1, just east of the town of Uvalde, the rate is 50 feet per mile. Still farther eastward, in Bexar County, from the Camp Bullis water well 22½ miles downdip to the Humble Oil and Refining Company's Oppenheimer No. 2, the rate is 35 feet per mile.

Using the highest of these rates, 50 feet per mile, we return to the nearest well to the Chittim field where the thickness of the Trinity is known. That is the Magnolia Petroleum Corporation's Wardlaw No. 1, in western Kinney County, where the thickness of that division is about 1,600 feet. Its distance from the Chittim field is 37 miles, giving an increase of 1,850 feet. The course is approximately with the dip. Adding to this increase the thickness of the division at the Wardlaw well gives an estimated thickness of 3,450 feet for the Trinity division in the Chittim field.

In that field the top of the Trinity division is approximately −3,690 feet. Adding to this depth the calculated thickness of the division gives the depth of −7,141 feet for the predicted base of the Trinity division in the Chittim field. That represents a depth of 7,956 feet from the surface. Subtracting this from 14,000 feet for the depth of the basement "in the vicinity of the gas wells" leaves 6,044 feet for the thickness of the pre-Trinity deposits. That would be of the same order as the thickness of the Jurassic and Neocomian deposits at comparable locations with reference to the margin of the basin in Arkansas.

The entire thickness of the Glen Rose, which the writer believes includes the lower Glen Rose, has been penetrated in two wells near the Chittim field. One of these is the Rycade Oil Corporation's Sullivan No. 5, four miles up the plunge from the field, which reached the base of the Glen Rose at the depth of −6,088 feet; and the same company's Chittim No. 2, two miles down the plunge from the field, which reached the same horizon at −6,890 feet. Proportioning the difference in these depths according to the respective distances of the two wells from the field gives −6,623 feet as the approximate base of the Glen Rose formation in the field. In the writer's opinion both of these wells were abandoned in the Hosston formation, so he believes that the depths given for the base of the Glen Rose really represent the base of the Trinity division, the deeper drilling being in the Neocomian.

On the assumption of the correctness of that belief, this last method of approach makes the base of the Trinity in the field 518 feet higher than the first method. It makes the Trinity division in the field 2,933 feet thick, and 1,333 feet thicker than it is in the Wardlaw well. That would give an average rate of 36 feet per mile for the thickening of the Trinity division between the Wardlaw well and the field, which is in better agreement with its average rate of thickening in that locality than the rate used.

Also should be considered the fact that the 14,000-foot depth of the basement is for the highest point or line on the structure, and that the slopes off structure on the basement are much steeper ("structure is much more accentuated") than the dips on the higher beds. Therefore, off the sides of the basement ridge the sedimentary section must be much thicker than it is over the top of that ridge.

NEW HORIZONS

Considered in the foregoing is about 550 miles of shore line in Texas, of which 300 miles is in South Texas. The sediments along this line are practically unexplored for oil and gas. Four of the included formations have produced oil in commercial quantities at places in East Texas, Louisiana, and Arkansas. These productive formations are the Smackover limestone, the Cotton Valley formation, the Hosston formation, and the Rodessa, Pine Island, and Sligo members of the lower Glen Rose.

In addition to the possibility of production from these formations in South Texas in stratigraphic traps and under structural conditions usually associated

with production, in some parts of the South Texas basin probably many salt domes await discovery and exploration. Salt domes seem to be located in the deeper parts of sedimentary basins, where source salt is available. If the reasoning is correct, South Texas has some of the deeper parts of the greater Texas Mesozoic basin.

Three salt domes in this region already are known—Piedras Pintas and Palangana in Duval County, and Gyp Hill, 35 miles south of these, in Brooks County. Numerous gravity minima in the south coastal area of Texas, and as far inland as Pescadito, east of Laredo in Webb County, are as probably salt domes as are similar minima east of the Brazos River, where salt has been found associated with a large proportion of them. In the deeper parts of this southern basin, such as the Nueces River geosyncline, probably they will be found inland almost to the Jurassic shore line as defined in this paper.

The Jurassic to lower Glen Rose seas, inclusive, contained islands and peninsulas which are now buried under younger sediments. Near-shore clastics surround them, and in some places these porous sediments are covered by impervious beds. The workers in Mexico have tentatively mapped some of these islands and peninsulas on the other side of the Rio Grande. Some are present in South Texas that are entirely without drilling exploration that was planned with that type of reservoir in mind. The test wells have been located on the top of the structures, but on many structures the reservoir traps may be on the flanks.

Probably some structures that have been condemned will be drilled again, and some of these may be proved productive. Probably the next important assignment for geophysical prospecting will be to learn how best to recognize and map buried coasts and buried peninsulas and islands, some of which may be large and small equivalents of the buried Nemaha Mountains.

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CLASSIFICATION OF FAULTS[1]

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ABSTRACT

A classification of faults based on the type of mechanical failure involved is proposed. The types recognized are: (1) normal diagonal shears, (2) reverse diagonal shears, (3) horizontal faults, (4) tension faults, (5) lateral shears, and (6) vertical shears. The types are diagrammed and, with the exception of vertical shears, are described on the basis of actual occurrences.

PURPOSE OF PAPER

The purpose of this paper is to suggest a classification of faults based on the type of mechanical failure involved, to describe the various types, and to indicate criteria for their recognition.

The entire argument for the proposed classification rests on the following premises: (1) faults represent failures, under stress, of the rocks of the earth's crust; (2) such failures are subject to the laws of mechanics; (3) consequently the type of failure developed affords direct evidence as to the nature of the stresses responsible for it.

The desirability of such a classification is obvious, since recognition of the true character of the stresses involved in faulting provides a clue to the correct interpretation of many of the associated problems of structural geology. The geologist attempting to analyze the forces responsible for structural phenomena has been handicapped by the fact that the only classification of faulting carrying any implication as to the nature of the forces involved was the broad classification of all faults as either "normal" or "reverse" (thrust).

The term "thrust," which has commonly replaced "reverse," obviously implies compressive stress. The term "normal" conveys no implication of itself; but the synonymous use of the terms "gravity" and "tension" carries not one but two different implications as to the forces responsible for "normal" faulting.

Undoubtedly a major factor in the existing confusion about the nature of the forces responsible for "normal" and "reverse" faulting has been the breadth of the definitions of those terms. While they must necessarily have been applied originally to certain definite types of structural failure, the classical definitions, "that a normal fault hades to the downthrow, whereas a reverse fault hades to the upthrow," leave only a vertical plane separating the two. Thus, the terms are all inclusive but not definitive from the standpoint of the forces or stresses involved.

That fact becomes apparent in the case of fault planes closely approaching the vertical which may wander from the "normal" to the "reverse" classification repeatedly with a few degrees change of the angle of hade. Several such instances

[1] Manuscript received, February 13, 1943. Presented by title before the Association at Fort Worth, April 7-9, 1943.

[2] Continental Oil Company.

are described by Clements.[3] Any attempt to attribute the "reverse" portions of a single failure of this type to compressive forces acting at right angles to the fault trace, and the "normal" portions to direct tension, for instance, obviously leads to an untenable position.

It is evident that as a basis of genetic classification, the terms normal and reverse are wholly inadequate, and that the types of structural failures represented by faulting in nature need to be more specifically defined. However, those terms are so thoroughly implanted in the literature, and in the minds of geologists, that any attempt to redefine them or discard them entirely could only lead to further confusion. It is proposed, therefore, to retain the terms, but relegate them to the status of descriptive adjectives indicating only the position of the fault plane with respect to the vertical.

Before proposing a new classification, it seems advisable to introduce a definition of faulting so that there may be no ambiguity in the discussions.

A fault may be defined as a break or fracture of the rocks of the earth's crust, accompanied by relative displacement of the rock masses on opposite sides of the fracture, along the plane of fracture.

The phenomenon of relative displacement or slippage along the plane of fracture is the distinguishing characteristic by which faults are differentiated from simple fractures such as mud cracks and joints. That characteristic at once suggests that faults are predominantly shearing failures, since engineering texts define a shearing stress as that stress created by two equal and oppositely directed forces applied normal to the axis of a specimen bar, but in different planes of action, so that any cross section of the bar between the planes of action tends to be displaced by sliding over the one next to it. With one exception, the types recognized in the proposed classification are shears; and in that exception the displacement is postulated to be essentially a gravity slumping following the break rather than a direct result of the stresses responsible for the failure.

Recognition of the following classes or types of faults is proposed.

1. Normal diagonal shears
2. Reverse diagonal shears (thrust faults)
3. Horizontal faults (bedding-plane shears)
4. Tension faults
5. Lateral shears
6. Vertical shears

The individual types are diagrammed; the forces and stresses involved are indicated and criteria for the recognition of the types established in the paragraphs which follow.

NORMAL DIAGONAL SHEARS

Normal diagonal shears are diagrammed in Figure 1. This type of faulting represents a diagonal shearing failure due to relative local uplift (or subsidence). This is probably the most common type of faulting in nature. It is the predomi-

[3] Thomas Clements, "Structure of Southeastern Part of Tejon Quadrangle, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 21, No. 2 (February, 1937), pp. 212–32.

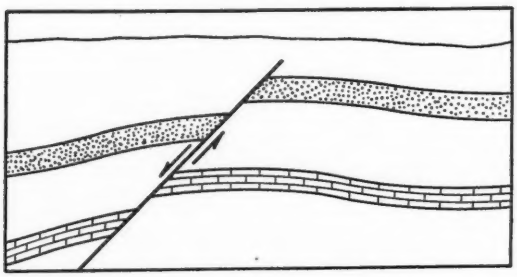

FIG. 1 - NORMAL DIAGONAL SHEAR.

nant type encountered in the oil fields of the Mid-Continent and Gulf Coast provinces of the United States, where the drilling of deep wells has provided an abundance of data concerning it.

Specific examples are: the faults forming the southern boundaries of the Fitts and Jesse oil fields in Oklahoma; the Rodessa fault in Arkansas, Louisiana, and Texas; the faults of the Powell-Mexia-Luling fault line fields of Texas; and much of the faulting encountered in the salt-dome type structures of the Gulf Coast province.

The forces and stresses involved are indicated in Figure 2.

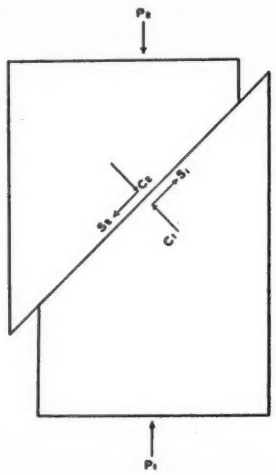

FIG. 2 - STRESS DIAGRAM NORMAL DIAGONAL SHEAR

Note that the forces of uplift (P_1), opposed by the weight of the overlying rocks (P_2), are resolved into shearing components parallel with the fault plane and compression components normal to that plane.

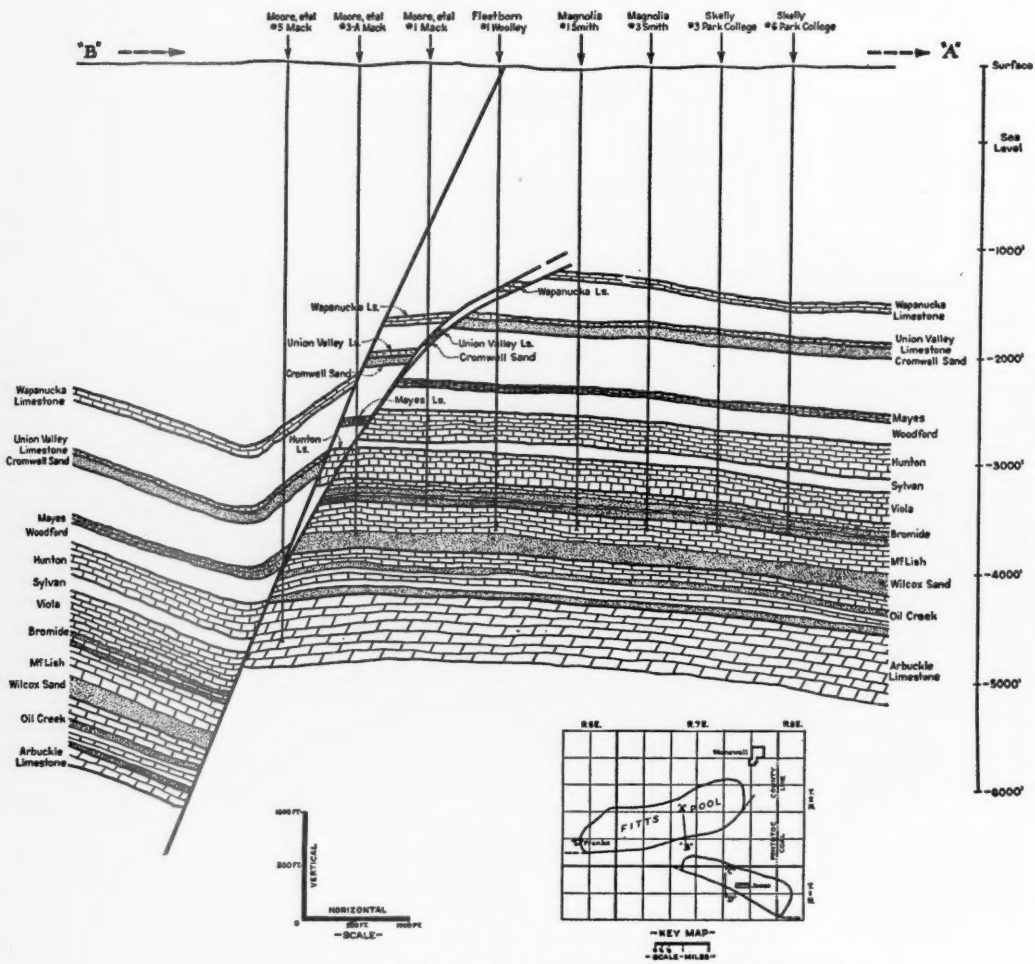

FIG. 3—*Normal Diagonal Shearing in the Fitts Oil Field, Pontotoc County, Okla.—Cross Section "A–B"*

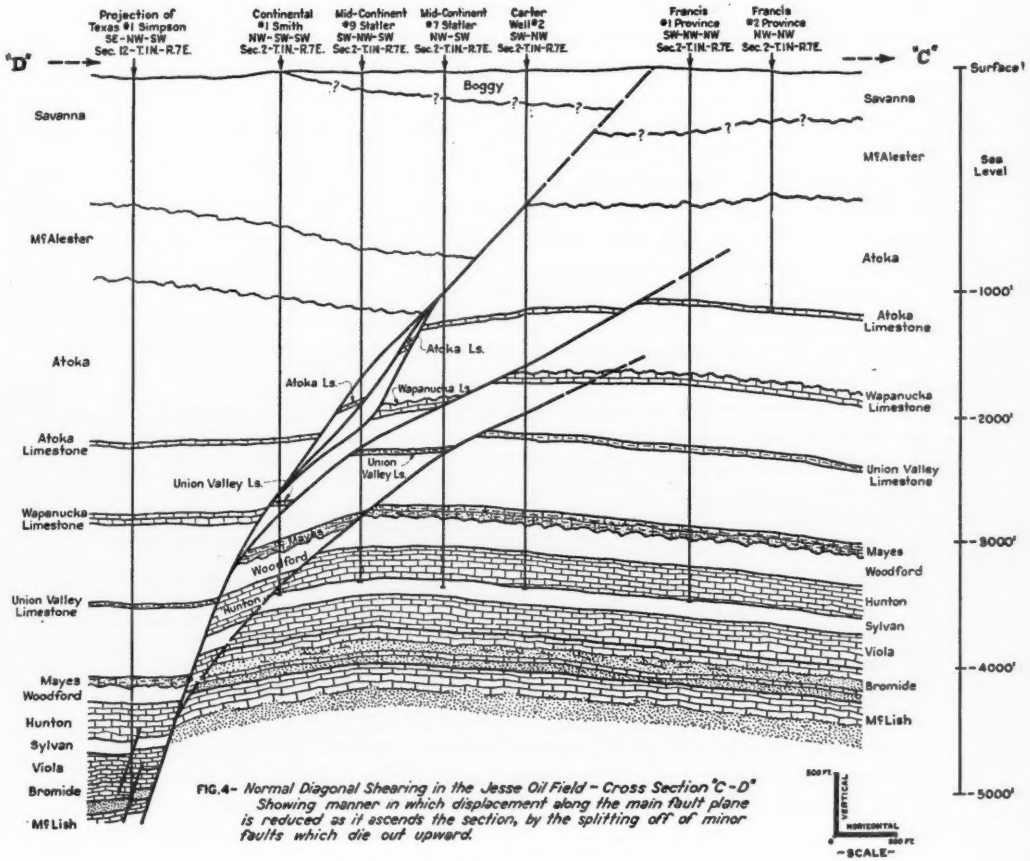

FIG. 4- *Normal Diagonal Shearing in the Jesse Oil Field - Cross Section "C-D" Showing manner in which displacement along the main fault plane is reduced as it ascends the section, by the splitting off of minor faults which die out upward.*

Reference to Figure 1 shows that the segment of rocks intersected by this fault has been extended horizontally. This effect has provided the basis for the argument that faulting of this type is a tension phenomenon. Actually, of course, the diagonal shearing also results in a corresponding vertical shortening of the intersected segment. So the question as to whether such diagonal shears are induced by horizontal tension or vertical compression must be settled on the basis of the observable facts and the physical limitations imposed by the character of the material.

The physical properties of the material involved rule out horizontal tension as the cause of normal diagonal shearing. Failures of that type can be produced by subjecting specimens of steel, of very high tensile strength as compared with its strength in shear, to direct tension. But rocks are generally strong in compression, weaker in shear, and very weak in tension. In limestone, for example, the shearing strength is approximately ten times the tensile strength. The maximum unit shearing stress that can be induced by either direct tension or compression occurs on a plane inclined at 45° to the direction of the applied forces, and is equal to only half the unit tensile or compressive stress on a plane normal to the applied forces. Consequently, rocks subjected to tension would develop failures in the form of fractures normal to the applied forces when the induced shearing stress had attained only a small fraction of their ultimate strength in shear.

Characteristic attributes or the criteria for recognition of normal diagonal shears are the following.

A vertical hole drilled through the fault plane encounters a loss of section equal to the amount of vertical displacement at the point where the fault plane is penetrated. This loss of section is the common means of recognition of these faults in drill holes and often serves to identify the type before evidence of the other attributes is available.

The fault plane is inclined at an angle that tends to approach 45° with the vertical (the angle of maximum induced unit shear) and seldom exceeds limiting angles of 30° and 60°.

The fault originates at depth and tends to die out upward. In other words, the displacement at depth tends to be greater than at higher positions along the fault plane. Lahee[4] has compiled figures on displacements on shallow and deep marker beds for a number of the fault-line fields of Texas which show this tendency quantitatively as well as qualitatively.

Cross sections of the Fitts and Jesse faults (Fig. 3 and Fig. 4), based on detailed studies of drill cuttings that permit accurate mapping of the faulting, show minor faults splitting off from the main fault, at lower angles of dip, and then dying out, thus accomplishing a piecemeal reduction of the displacement as the fault ascends the stratigraphic section.

This tendency to die out upward is in accordance with the stress interpretation previously outlined, since, for rocks with a certain shearing strength, there would

[4] Frederic H. Lahee, "Oil and Gas Fields of the Mexia and Tehuacana Fault Zones, Texas," *Structure of Typical American Oil Fields*, Vol. 1, Amer. Assoc. Petrol. Geol. (1929), p. 353.

be a minimum thickness of overburden capable of producing shearing in the underlying beds, even with the aid of impact loads.

Many of the observable portions of the fault plane closely approach a true plane surface, but where persistent change in the attitude of the surface is found, the tendency seems to be toward steeper dip with greater depth. This probably can be attributed to a gradually increasing component of vertical shear with increasing depth, and a consequent slight change in the angle of maximum unit shear.

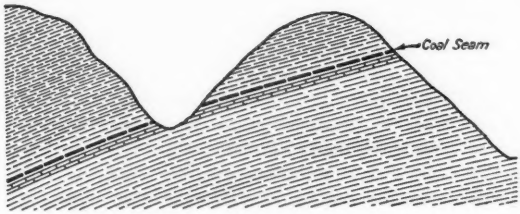

FIG. 3-A- *Site of Durango, Colorado Slide Showing Coal Seam in Inclined Strata*

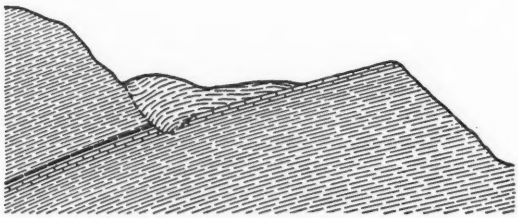

FIG. 3-B- *Durango Slide - Showing manner in which overlying material slid down inclined bedding plane into ravine, when burning of coal seam reduced the shearing strength parallel to the bedding.*

In connection with this type of fault, one special case of surficial rather than deep-seated faulting must be noted. It is the landslide, which belongs in the general class because it represents a normal diagonal shearing failure. However, it is decidedly a special case requiring elevated topographic position and lack of lateral support. The initial failure is ordinarily made possible by a reduction in the shearing strength of the material along the incipient fault plane, as by the soaking of shale with water, thus permitting the force of gravity to precipitate the slide without contemporaneous uplift or subsidence of adjacent rocks. It should be recognized, however, that its relation to the general class ends with the initial failure, after which the displaced segment is simply a free body traveling like a sled. The course it follows is governed by the surface on which it rides and may generally be expected to flatten where the slide comes to rest.

The so-called moving mountain south of Durango, Colorado (Fig. 5), provides an interesting and rather exceptional instance of a slide in which the burning of a coal seam beneath one lobe of an escarpment in strata inclined at an angle of about 30°, furnished the reduction in resistance to shear needed to initiate the slide.

It may be noted that in this instance the slippage occurred along the bedding planes, and that the tilted attitude of the strata was a contributing factor in the

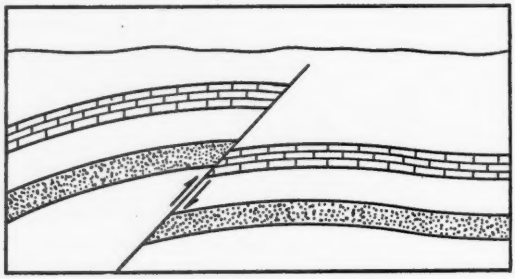

FIG.6-REVERSE DIAGONAL SHEAR

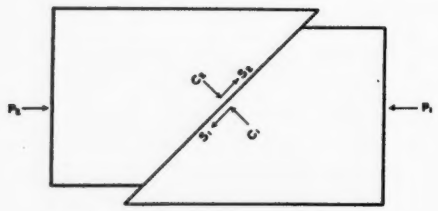

FIG.7-STRESS DIAGRAM REVERSE DIAGONAL SHEAR

development of the slide. The presence of a steep-sided ravine back of the lobe of strata involved provided the other factor necessary; that is, the lack of lateral support. The slide finally came to rest in that ravine, the material in the leading portion bulging up into a large mound under the impetus of the following mass.

Because of the special circumstances required for its development, the landslide may not properly be used as the basis of generalizations regarding normal diagonal shears as a class.

REVERSE DIAGONAL SHEARS (THRUST FAULTS)

Reverse diagonal shears are diagrammed in Figure 6. This type of faulting represents a diagonal shearing failure due to approximately horizontal compressive stresses, or in the case of stratified rocks, of stresses transmitted along the bedding planes.

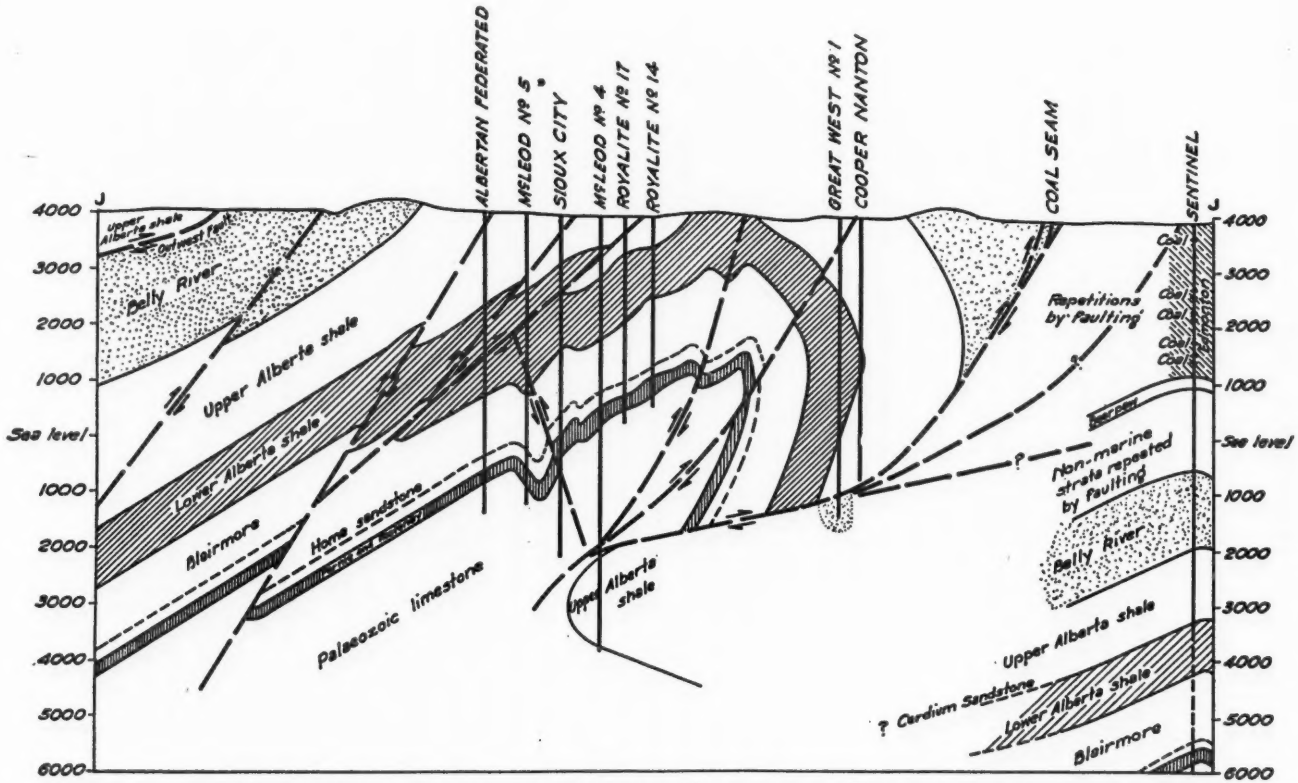

FIG.8- AN EAST-WEST CROSS SECTION THROUGH THE TURNER VALLEY OIL FIELD. ALBERTA, CANADA.
Showing reverse diagonal shearing faults associated with an overturned fold.
From Canadian Geological Survey Paper. 38-22.

A point to be noted particularly in connection with the stress analysis of Figure 7 is that mechanically the reverse diagonal shear is identical with the normal diagonal shear except for the direction of the applied stress.

A cross section through the Turner Valley field, Alberta, Canada (Fig. 8), provides illustrations of reverse diagonal shearing, associated with some overturning of strata, as determined from data furnished by drill holes and surface evidence.

One characteristic of this type of fault is that a vertical hole drilled through the faulted segment encounters an increased thickness of beds, as compared with the normal section, due to the repetition of beds, since the hole, in crossing the fault plane, passes from stratigraphically lower strata above, into stratigraphically higher strata below. Conclusive evidence of such a repetition of section may demonstrate the presence of reverse diagonal shearing, in a single drill hole, when data about other characteristics are lacking.

With the compressive forces applied horizontally, the plane of maximum unit shearing stress is inclined at an angle of 45° from the horizontal. However, the total shear increases at angles of dip below 45°; and since the shearing strength parallel with the bedding is ordinarily much lower than at right angles to the bedding, the failure commonly occurs at an angle less than 45°.

Theoretical considerations indicate that the failure should be initiated at the surface and that this type of faulting presumably dies out at depth, although that depth may be beyond present observation. However, if the compressive stresses originate as the result of the downwarping of a narrow basin and the uplift of adjacent masses, it is obvious that the uppermost strata in the basin will be subject to the most severe compressive stresses; whereas, successively lower beds will be stressed in progressively lower degree. The decreasing horizontal compression, and the increasing vertical pressure with increased thickness of overburden, mean decreasing reverse diagonal shearing stress and increasing opposed normal diagonal shearing stress.

While definite downward limits would necessarily vary with the magnitude and mode of origin of the horizontal compression, the foregoing considerations strongly suggest that reverse diagonal shears, like compression folds, tend to die out at depth.

Massive rocks subjected to compression tend to fail by shearing without other deformation. But where relatively thin hard rocks are interbedded with softer shales, the hard rocks act like struts in transmitting the compressive stresses. If the effective slenderness ratio of these struts, including such stiffening effect as is furnished by the confining shales, is high enough, the initial failure may be by buckling rather than by shearing. In that case, a compression fold develops which may be sheared off at any stage from a slight buckle to an overturned fold. Obviously the fault plane may intersect the bedding planes at any angle in such cases, but it should still be inclined from the horizontal, and from the approximate attitude of the bedding planes before the buckling occurred.

HORIZONTAL FAULTS (BEDDING-PLANE SHEARS)

This classification of horizontal faults includes all faults in which masses of strata have been displaced along shearing planes approaching the horizontal. Since such displacements ordinarily occur along the bedding planes of stratified rocks, they may also be designated as bedding-plane shears.

Minor displacements of this type are probably of common occurrence, although they are naturally difficult to recognize, since the apparent relations of the strata above and below the fault remain unchanged.

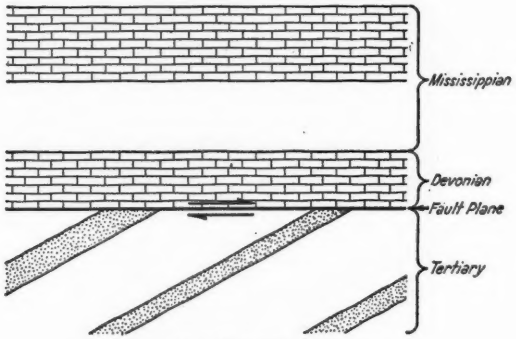

FIG. 8.- *Horizontal Shear*
Phenomenon of older rocks overlying younger strata identifies material in older beds as an overriding mass, and demonstrates movement along a horizontal fault plane.

However, many major displacements of this class have been recognized because the overriding mass has transgressed upon younger rocks or over ancient topography. Such displacements are diagrammed in Figure 9. They have generally been called overthrusts.

The mechanics of the minor displacements are relatively simple, but those of the major ones are still somewhat obscure.

In the simpler cases, it has previously been noted that the downwarping of strata in a narrow basin sets up greater compressive stresses in the upper beds than in the lower ones. To the extent by which such compressive stresses in the upper bed exceed those in the lower one, shearing stresses are developed along the bedding planes.

It has also been noted that the shearing strength of stratified rocks is ordinarily less, parallel with the bedding planes than perpendicular to them. In fact certain combinations of strata, such as massive limestones separated by clay shales, provide situations where that difference in resistance to shear is so great as to make the shale virtually a lubricant for differential movement along the bedding planes between the overlying and underlying limestones.

Because of this comparative ease of movement, many minor adjustments undoubtedly take place along the bedding planes which are not recognizable as definite faults.

However, in instances where resistance to movement by the overlying bed is also less, either due to its outcrop or to the development of reverse diagonal shearing cutting down through it, observable displacement may develop along the bedding planes.

Thus faults initiated as reverse diagonal shears may develop into bedding-plane shears where suitable lubricating strata are present. In fact, some such

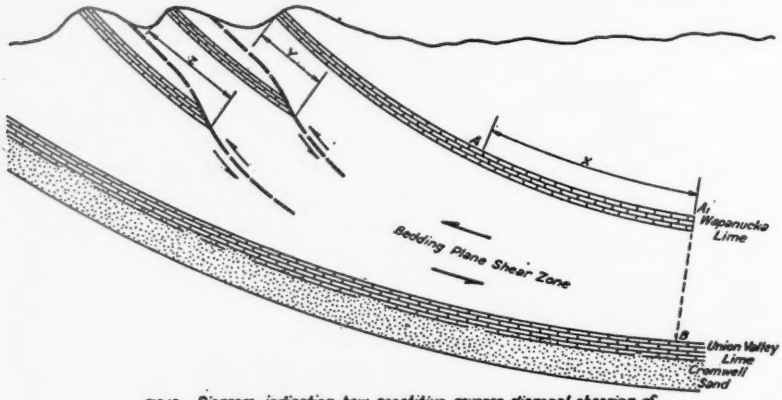

FIG. 10- *Diagram indicating how repetitive reverse diagonal shearing of a thin limestone bed is presumed to pass into a bedding plane shear in the shale section above the next lower competent bed. Displacement "X" of point "A" from its original position "A'" with respect to "B" must be greater than the sum of "Y"+"Z" by the amounts removed from outcrops by erosion.*

transition (on a piecemeal basis when no conspicuous lubricating layers are present) probably represents the mechanics of the process by which reverse diagonal faults die out with depth.

In discussing the structure of the western part of the Ouachita Mountains in Oklahoma, Hendricks[5] states:

> South of the Windingstair fault most of the overthrust blocks slid on Womble shale (Ordovician) or Middle Stanley shale (Pennsylvanian). Between the Windingstair and Ti Valley faults the gliding surfaces are the Johns Valley shale or shale in the lower part of the Atoka formation (both Pennsylvanian). Between the Ti Valley and Pine Mountain faults the gliding planes are Caney shale (Mississippian) or shale in the lower part of the Atoka formation (Pennsylvanian) north of the Pine Mountain fault, shale in the Springer formation or the lower part of the Atoka formation (both Pennsylvanian) constitutes the gliding planes.

[5] Thomas A. Hendricks, "Structure of the Western Part of the Ouachita Mountains." Presented by title before the Association at Chicago, April 10–12, 1940.

Figure 10 diagrams a situation such as occurs back of the Choctaw fault, in which the Wapanucka limestone-Caney shale section is repeated several times at the outcrop.

The explanation of the situation appears to be that as the Wapanucka limestone is forced into an elevated position by thrust from the right, sufficient potential energy is eventually developed, and transmitted back along the limestone bed acting as a strut, to cause a reverse diagonal shearing failure extending through the limestone and into the underlying shale. Continued thrust from the right results in the advancing segment of Wapanucka together with some of the "lubricant" Caney shale riding up the inclined surface of the preceding static segment. When sufficient resistance has been developed, another reverse diagonal shear occurs in the competent bed and the same cycle is repeated.

Thus, it seems evident that the displacement of the Wapanucka with respect to the underlying beds, along the bedding planes, back of this series of diagonal shears must be approximately equivalent to the sum of the displacements along the diagonal fault planes.

The instances of bedding-plane shears thus far discussed are definitely overthrusts.

The Heart Mountain "overthrust" near Cody, Wyoming, provides an example of the major displacement of large rock masses along a fault plane which is now approximately horizontal.

Pierce[6] describes the overriding mass as including the Bighorn dolomite (Ordovician), dolomites, limestones, and shales of Devonian age and the Madison limestone (Mississippian) with a combined thickness of not more than 1,700 feet. The thickness of existing masses generally ranges from 700 to 1,000 feet; the beds lie nearly horizontal; the maximum displacement is calculated as 34 miles, movement being generally from west to east. The greater part of the area transgressed was an erosion surface of low relief.

The remnant masses in some localities are reported as cut by high-angle faults which do not extend into the underlying rocks and are presumably the result of adjustments during the emplacement of the overriding strata. Otherwise they are apparently little disturbed except where involved in subsequent folding or faulting.

The source of the supposed thrust is admittedly unknown.

That fact, together with the apparent lack of extensive reverse diagonal shearing, makes it seem incredible that these strata were actually thrust forward solely by pressure from the rear over an approximately level surface for such a distance, to say nothing of being propelled upgrade in some localities.

Regardless of whether the initial superposition of these masses came as the result of reverse diagonal shearing, or of a phenomenon similar in type to the Durango slide, the cross-country migration of the masses with so little disturb-

[6] William G. Pierce, "Heart Mountain and South Fork Thrusts, Park County, Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 11 (November, 1941), pp. 2021–45.

ance would seem far more plausible as an effect of creep down an inclined surface, with the force of gravity operating to accelerate every individual particle, than it does as a result of thrust from the rear transmitted through the strata involved for a distance of 30 miles. Even if a very low coefficient of static friction is assumed, it seems inevitable that the thrust required to force such a mass over a level surface would build up stresses in excess of the shearing strength of the limestones within a distance of a very few miles, and that extensive reverse diagonal shearing would consequently occur within the overriding mass.

In reviewing the evidence, it is clear that faults in this class are generally the result of shearing stresses acting parallel with the bedding planes; but it does not follow that those stresses always originate in the same manner.

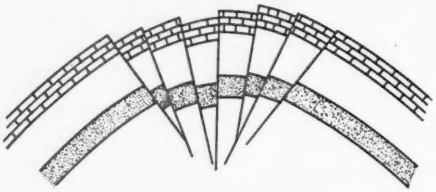

FIG. 11- *TENSION FAULTING*

In some cases they undoubtedly develop as the result of a differential between the thrusts affecting the strata above and below. In such cases they are ordinarily associated with reverse diagonal shearing, and the mass above the fault plane is literally an overthrust mass.

At the other extreme are cases such as the Durango slide where a normal diagonal shear developed along the bedding planes in steeply inclined strata.

Between those two extremes there is a wide range of possible combinations of thrust and gravitational acceleration down less pronounced inclines, with subsequent reversal of the tilt leaving the fault plane horizontal.

In case of doubt as to the actual motive force, it would seem desirable to designate the displaced strata above the fault plane as the overriding mass rather than an overthrust.

TENSION FAULTS

Tension faults are diagrammed in Figure 11. This type represents direct-tension fractures approximately normal to the bedding and to the direction of the applied stress, and consequent gravity slumping of the segments involved. A pseudo-shearing effect is thus created which brings the phenomenon within the definition of faulting; although the relative displacement on opposite sides of the break is, in this instance, presumed to occur subsequent to the fracture and as the result of entirely different forces rather than as inherent in the failure as is the case in true shearing.

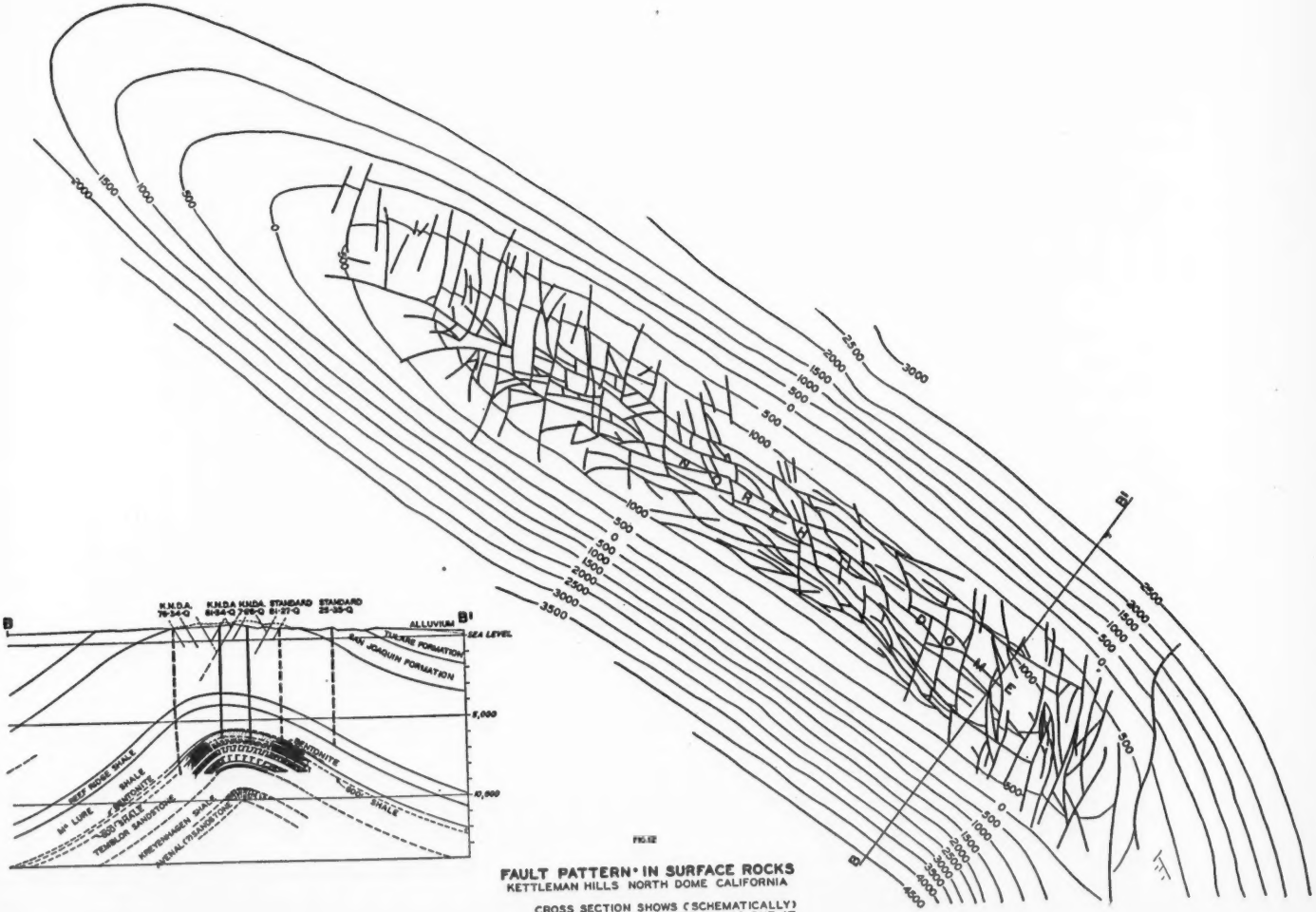

FIG. 12

FAULT PATTERNS IN SURFACE ROCKS
KETTLEMAN HILLS NORTH DOME CALIFORNIA

CROSS SECTION SHOWS (SCHEMATICALLY) MANNER IN WHICH FAULTING DIES OUT AT DEPTH.

AFTER W.P. WOODRING AND RALPH STEWART.

Tensile stresses are not prevalent over widespread areas. They tend to develop only locally, and the weakness of rocks in tension precludes their transmission over great distances. However, tensile stresses can be developed locally over anticlinal flexures and where the folding is sharp enough tension faulting may occur.

Their essential characteristics may be deduced from the conditions requisite for their occurrence. Since the tensile stresses in upward-arched strata are greatest in the uppermost layers, and diminish downward, the faults must originate at the surface and die out at depth. They should be "normal" in aspect, although the attitude of the fault planes would be governed by the attitude of the strata and in some cases might be practically vertical. They tend to occur in groups rather than as a single break, with the fault pattern indicating the direction of stress.

The general failure of the literature to recognize this as a distinct type of faulting and to differentiate between it and normal diagonal shearing makes it impossible to make many positive statements about the occurrence of the type.

Barnes[7] is authority for the statement that the pattern of surface faulting on the Kettleman Hills North Dome (Fig. 12) is of this type, and that the numerous faults shown at the surface die out with depth.

It may be noted that the surface faults are arranged in quite definite groups. One group parallels the axis of the anticline and is distributed across the crest of the fold, that is, the zone of maximum transverse flexure. The other two groups extend at right angles to the axis of the anticline, and occur near each end of the crest, which is relatively flat in the intervening area. In other words, these faults are concentrated in the zones of maximum longitudinal flexure.

Woodring, Stewart, and Richards[8] describe the group paralleling the axis as generally dipping toward the axis at angles averaging about 60°, with the axis lying in the structurally lowest part of a complex fault trough extending along the crest of the fault.

The collapsed crest situation which is pictured, together with the high-dip angles of the fault planes, as high as 70°–80° in some instances, their persistent inclination toward the axis, and the disappearance of the faulting at depth seem to establish this group as tension faults beyond any reasonable doubt.

LATERAL SHEARS

The classification of lateral faults includes shearing failures, along planes which closely approach the vertical and in which the relative displacement is primarily lateral, any vertical displacement involved being merely incidental to the lateral movements. Thus in plan view the fault is diagrammed as in Figure 13.

[7] R. M. Barnes, personal communication.

[8] W. P. Woodring, Ralph Stewart, and R. W. Richards, "Geology of the Kettleman Hills Oil Field, California," *U. S. Geol. Survey Prof. Paper 195* (1940), p. 150.

Within recent years the terms "tear fault" and "shear" or "transverse fault" have been applied to faults which presumably belong in this class. Instances are cited by Pierce.[9]

None of those terms seems well adapted, since "to tear" means literally to pull or rip apart and suggests tension; shear is literally applicable to all but one of the types of faults recognized; and transverse is a term which might well be used to indicate the position of a fault trace or fault plane in relation to some other geologic or topographic feature, but has no meaning otherwise.

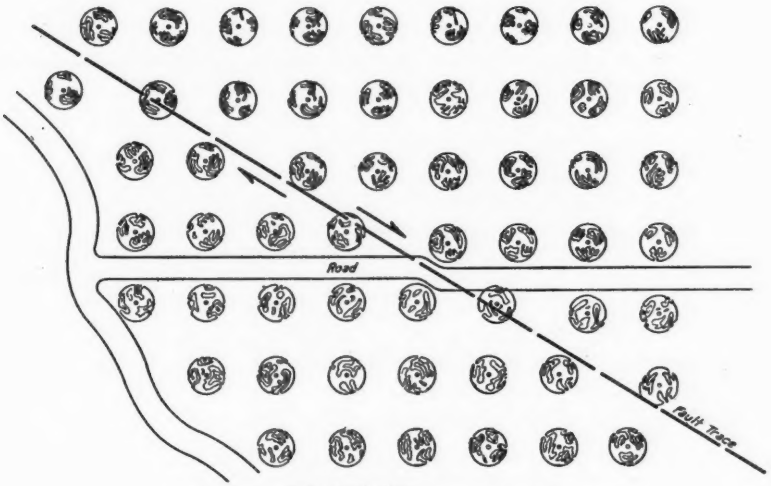

FIG. 13.—Lateral Shear
Plan View Diagram Showing Lateral Displacement of Tree Rows in Orange Grove near Calexico, California as Result of Recent Faulting. Based on Aerial Photograph Published in Life Magazine.

On the other hand, a lateral shear or a lateral shearing fault can be interpreted only as meaning a sidewise shear, or one in which the relative displacement on opposite sides of the fault is primarily sidewise.

The outstanding example of this type of faulting in the United States is the San Andreas fault in California.

This great fault is traceable for a distance of more than 500 miles from the Mexican border northwest to Punta Arenas on the coast of northern California, where it disappears beneath the ocean.

Eaton[10] describes a part of it in the following terms.

[9] William G. Pierce, *op. cit.*, pp. 2036–37.

[10] J. E. Eaton, "Decline of Great Basin, Southwestern United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 1 (January, 1932), p. 25.

The San Andreas rift is a shattered zone a mile wide near its center and narrower toward the ends, composed of long, parallel slivers separated by faults. A differential rising and falling of adjacent slivers locally ponds the drainage and results in a line of small, saline lakes. The slivers commonly expose rocks of different kinds and ages, partly because of local vertical movement between them, and partly because of horizontal offsetting. The amount of vertical throw differs greatly along the rift, being here little, and there as much as 5 miles. It scissors from side to side, being merely incidental to the greater horizontal movement. The horizontal throw is distributed in steps among several closely spaced parallel slivers, a few of which commonly show more recent activity than the others. Individual fractures branch from the rift at low angles, their throw commonly decreasing in short distances as they diverge from the main line of adjustment.

He also estimates the post-Miocene displacement of the southwest side as 24 miles plus, northwestward relative to the northeast side; and he ascribes a similar estimate to Noble. Offsetting of drainage lines is cited as evidence of relatively recent displacement as much as 5,400 feet.

Noble[11] describes the topographic expression of the fault as:

A continuously traceable chain of scarps, trough-like depressions and ridges which afford clear and unmistakeable evidence of recent earth movements. This line of topographic features, which is so straight that one may sight along it for distances of 25 miles or more, marks the position of a profound fault in the underlying rocks. This straight and continuous fault is the San Andreas fault—unquestionably the master fault. Bordering the master fault is a belt of roughly parallel branching and interlacing fractures which in places attain a width of six miles.

The bordering belt he designates as the "fault zone" and the main fault and border belt together as the San Andreas rift.

Other significant statements from the same source are:

The evidence of the nature of the fault movements is somewhat conflicting; the dominant structure is a sort of slicing which appears to be mainly the result of horizontal[12] shear along the San Andreas fault. No exposures of the fault plane are obtainable, but the straight course of the fault across an uneven topography suggests that it is nearly vertical.

The latter statement is worthy of special notice, as it calls attention to an identifying feature of lateral shears, namely, that their surface traces will follow a straight line over topographic features of large relief, whereas the traces of inclined faults would necessarily be sinuous under similar conditions.

The San Francisco earthquake of April 18, 1906, was the result of slippage along the northern portion of the San Andreas fault. That catastrophe directed attention to the fault and led to recognition of its character as a great plane of shear.

According to Willis,[13] the movement on that occasion involved horizontal displacement of 21 feet, as against vertical displacement of only 1½ feet.

[11] L. F. Noble, "The San Andreas Rift and Some Other Active Faults in the Desert Region of Southern California," in "Report of the Advisory Committee in Seismology," *Carnegie Inst. Washington Year Book 25* (1925–26), pp. 416–22.

[12] Presumably means lateral rather than horizontal.

[13] Bailey Willis, "Folding or Shearing, Which?" *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 1 (January, 1927), p. 38.

A résumé of the evidence indicates clearly that this fault represents an example of lateral shearing with primary lateral displacement and only incidental vertical displacement. Measurable displacement has occurred within 35 years; geologically recent lateral displacements of hundreds of feet are indicated by the courses of present stream channels; and displacements of many miles are suggested by the boundaries of geological formations. While the total displacement as the result of the earlier movements may never be accurately determinable, the magnitude of this structural feature as indicated by its linear extent and the amount of incidental shearing accomplished within its border zones indicates that it must have been of great magnitude.

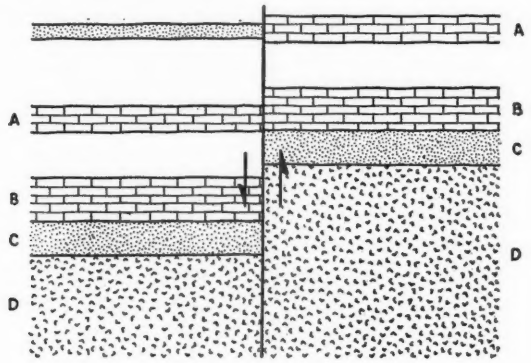

FIG. 14.—*Vertical Shear Diagrammed in vertical cross section normal to fault plane.*

The criteria for the recognition of lateral shears may readily be inferred from the foregoing discussions. They include evidence of lateral displacement and verticality of fault plane. While not a positively essential feature, all instances of "scissors" faulting, that is, faults in which the upthrow is first on one side of the fault plane and then on the other, should be suspected of being lateral shears. The "scissors" phenomenon is incompatible with either normal or reverse diagonal shearing; but would be the natural result of incidental vertical displacements due to buckling along the sides of a lateral shearing failure.

VERTICAL SHEARS

It is theoretically possible for vertical shearing, resulting primarily in vertical displacement, to occur as the result of differential uplift, *under sufficient thickness of overburden*. Mathematical analysis indicates that burial to a depth of approximately 40,000 feet is necessary for that type of failure to be initiated in solid homogeneous limestone. Less competent beds should develop such failures at lesser depths.

This type of vertical shear would be diagrammed as in Figure 14.

Since it is postulated that vertical shears should develop only at considerable depth below the surface, it follows that any actually appearing at the surface should be in areas from which great thicknesses of material have been removed by erosion.

No specific instance of visible faulting is known to the writer which can be positively assigned to this class. However, the occurrence of such failures is believed to be a mathematical certainty. They presumably occur at great depth as the initial fracture resulting from differential uplift, above the zone of flow or molecular readjustment, and as the progenitors of normal diagonal shears at lesser depth.

The transition from vertical shearing to normal diagonal shearing is presumably a gradual one with the dip of the fault plane determined by the resultant of a vertical shearing component varying in proportion to the square of the distance beneath the surface, and a diagonal shearing component varying directly with the depth.

CONCLUSIONS

In reviewing the preceding discussions, it may be noted that the ever present force of gravity plays an important part in the development of normal diagonal shears; is responsible for the displacements in tension faulting; probably controls the development of repetitive reverse diagonal shears; and may have been a contributing factor in the development of many of the major horizontal faults. Consequently, the term gravity fault, which has appeared frequently in geological literature, seems too ambiguous to be of value, and its abandonment is suggested.

Some statements of an admittedly speculative nature have been incorporated in the foregoing discussions because the reasoning has been from the theoretical to the actual on the basis of the laws of mechanics, and time has not permitted the travel necessary for original study of every type of fault. Moreover, the lack of such a sytem of classification as is here proposed leaves critical information lacking regarding many faults described in the literature.

This classification may not be fully adequate to cover all the faulting which occurs in nature. Nor will its adoption assure the immediate classification of every fault examined in the future, since in many places the faults themselves are obscure, and some structural situations are so complicated as to make the deciphering of original causes virtually impossible.

However, it does offer a relatively simple classification which covers the majority of fault types to be found. Since it is based on the stresses responsible for the failure, its general adoption should stimulate the examination of faults for diagnostic criteria as to type, and tend to promote logical reasoning and more uniformity of conclusions regarding the mechanics of faulted structures.

ACKNOWLEDGMENTS

In addition to the references to published material, acknowledgments are due to W. Baxter Boyd, whose detailed studies of the faulting in the Fitts and Jesse pools provided valuable additions to the information available on normal diagonal shears; to C. W. Tomlinson; Roy M. Barnes; J. V. Howell; and others who in discussion and by correspondence have advanced ideas and furnished material during the years that this paper has been in preparation, which constitute a substantial part of the background for the proposed classification.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 27, NO. 9 (SEPTEMBER, 1943), PP. 1268-1272

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library, and are available, for loan, to members and associates.

NOTE ON THE PRESENT KNOWLEDGE OF THE TERTIARY SEQUENCE IN PAPUA AND THE MANDATED TERRITORY OF NEW GUINEA, BY IRENE CRESPIN

REVIEW BY BURTON WALLACE COLLINS[1]
Auckland, New Zealand

"Note on the Present Knowledge of the Tertiary Sequence in Papua and the Mandated Territory of New Guinea," by Irene Crespin. *Proc. Sixth Pacific Sci. Cong.*, Vol. 2 (1940), pp. 529, 530. (Commonwealth of Australia, Dept. Interior, Geol. Branch, New Ser., Pub. No. 1.)

Since the island of New Guinea and its environs at the present time hold one of the foremost positions in the interest of the world it may be worth while to draw the attention of American geologists, even at this late stage, to a short paper on the geology of the island published several years ago by Miss Irene Crespin, Government paleontologist to the Commonwealth of Australia. Not only is New Guinea at the time of writing of interest as one of the most active battlefields of the Pacific sector of the war, but of prime importance is the possibility of producing oil in this island, by reason of its nearness both to Australia and New Zealand and to what may become in the near future a major war zone.

As the original paper may not be readily available to many of those interested, its salient points are summarized here. Dr. Crespin begins by stating that:

> No concise account of the Tertiary geology of Papua and the Mandated Territory of New Guinea is at present available. . . . During the last ten years, geologists of oil companies have made fairly extensive surveys in various parts of the two areas. As the information derived from these investigations is not available for general consideration, little correlative work has been possible. Geological explorations can only be undertaken with great difficulty, owing to the inaccessibility of the country. Outcrops are few except along river valleys, and high mountain ranges traverse the island from east to west. Moreover, some of the native tribes are unfriendly.

Summarizing present knowledge, she states:

> The most important feature of the Tertiary geology of Papua and New Guinea is the similarity of the Tertiary foraminiferal, coral, and molluscan faunas with those of the Netherlands East Indies. The sequence appears to be the same, and the terminology used in the classification of the Tertiaries of the Dutch East Indies can be applied to the areas under consideration.

Eocene rocks, *in situ*, are poorly developed in the Mandated Territory. They are known to occur, however, along the Sepik divide toward the border of Dutch New Guinea, and on the Wahgi plateau. Rocks of this age have been determined in southeastern Papua especially near Port Moresby. Foraminifera found include: *Camerina*, *Assilina*, *Discocyclina*, *Biplanispira*, *Pellatispira*, and *Borelis*.

Oligocene beds have been recorded from only a few localities. *Lepidocyclina* and reticulate *Camerina* are found.

Lower Miocene (Aquitanian, stage "e" of East Indian Tertiary) rocks are moderately well developed in both territories. One of the best known localities is Bootless Inlet, near Port Moresby, where large eulepidines are abundant in limestone. On Tumleo Island, off the coast of Aitape, North-east New Guinea, a limestone is composed almost entirely of tests of *Spiroclypeus*. Another characteristic foraminiferal genus, present in another locality, is *Miogypsinoides*.

[1] P.O. Box 10, Auckland, New Zealand. Formerly of The Island Exploration Company, Madang, Territory of New Guinea. Manuscript received, July 10, 1943.

Middle to lower Miocene (Burdigalian, stage "f") rocks are well represented in both territories. Characteristic foraminiferal genera include: *Lepidocyclina, Trybliolepidina, Miogypsina, Katacycloclypeus, Alveolinella bontangensis;* without *Eulepidina* and *Spiroclypeus.*

Mio-Pliocene (top of upper Miocene to lower Pliocene, roughly equivalent to stage "g" of East Indies) rocks are extensively developed in both territories, especially in the Delta and Gulf divisions of Papua and in the Finsch Coast series of New Guinea. They are characterized by the absence of larger foraminifera, but the smaller types occur abundantly in mudstones, which in some places are of considerable thickness. Mollusca are also well represented.

Upper Pliocene and later sediments of New Guinea can not be correlated accurately with deposits in the East Indies. Beds containing more than a certain percentage of recent mollusca are, hence, by Miss Crespin, arbitrarily placed in the Pleistocene.

Upper Pliocene sediments are, on this basis, represented in Papua by mudstones containing smaller foraminifera, certain of the rotalines being typical. In the eastern part of the territory, beds with a rich upper Pliocene molluscan fauna occur at Cape Possession. In New Guinea, beds equivalent to the upper Wanimo series are of the same age.

Pleistocene rocks consist chiefly of chalky coral limestones with foraminifera which are typical of the tropical seas and shorelines of the present day. They appear to be best developed toward the east of New Guinea and in the adjacent islands, including New Britain.

The appended list of papers (mainly on the geology and geography of New Guinea and the Solomon Islands) is necessarily incomplete. It is confined (with two or three exceptions) to papers published in English during the last 20 years.

PAPERS ON GEOLOGY OF NEW GUINEA

1. ANDREWS, E. C., "Notes on the Structural Relations of Australasia, New Guinea, and New Zealand," *Jour. Geol.*, Vol. 24 (1916), pp. 751–76.
2. ANGLO-PERSIAN OIL COMPANY, *The Oil Exploration Work in Papua and New Guinea Conducted by the Anglo-Persian Oil Company on Behalf of the Commonwealth of Australia, 1920–1929*, 4 vols., 2 atlases. London (1930).
3. AUSTEN, L., "The Delta Division of Papua," *Australian Geographer*, Vol. 2, No. 4 (1934), pp. 20–27.

3a. ———, "The Trobriand Islands of Papua," *ibid.*, Vol. 3, No. 2 (1936), pp. 10–22.

4. BEARUP, A. J., "The Ramu and Wahgi Valleys of New Guinea," *ibid.*, Vol. 3, No. 1 (1936), pp. 3–14.
5. BEMMELEN, R. W. VAN, "The Geotectonic Structure of New Guinea" (abstract), *Rept. Australian and New Zealand Assoc. Adv. Sci.*, Vol. 24 (1939), p. 94. *Mijnbouw en Geologie Mijningenieurb.* 2 (1939), pp. 17–27.
6. BERNATZIK, H. A., "A Flight into the Stone Age: Life in Unexplored New Guinea," *Geog. Mag.*, Vol. 2, No. 2 (1935), pp. 75–93.
7. BLACKWOOD, BEATRICE, "Life on the Upper Watut, New Guinea," *Geog. Jour.*, Vol. 94, No. 1 (1939), pp. 11–28, maps, illus.
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NOTES ON THE EARLY HISTORY OF WATER-WELL DRILLING IN THE UNITED STATES, BY CHARLES W. CARLSTON

REVIEW BY JOHN L. FERGUSON[1]
Tulsa, Oklahoma

"Notes on the Early History of Water-Well Drilling in the United States," by Charles W. Carlston. *Econ. Geol.*, Vol. 38, No. 2 (Chicago, Illinois, March-April, 1943), pp. 119–36.

Those who are interested in the beginnings of the petroleum industry will enjoy and benefit from reading this preliminary report on the early drilling for water in the United States.

[1] Amerada Petroleum Corporation. Review received, July 30, 1943.

Exhaustive research has furnished material for an accurate historical record of the initiation and growth of this important activity, with particular attention being given to the development of new techniques and equipment.

The report covers the first American efforts to drill for salt and fresh water in the Ohio Valley and the East. Subsequent developments, since approximately 1825, are discussed in the states of the deep South only.

Several illustrations of early drilling rigs and tools are included, together with eye-witness accounts of historically important drilling operations.

EOCENE FORAMINIFERA FROM THE TYPE LODO FORMATION, FRESNO COUNTY, CALIFORNIA, BY LOIS T. MARTIN

REVIEW BY MERLE C. ISRAELSKY[1]
Houston, Texas

"Eocene Foraminifera from the Type Lodo Formation, Fresno County, California," by Lois T. Martin. *Stanford Univ. Pub.*, Univ. Ser., Geol. Sci., Vol. 3, No. 3 (1943), pp. 95–125, Pls. 5–9.

This excellent paper lists the foraminifera from 59 samples taken from 1,100+ feet of the type section of the Lodo formation and a near-by supplementary section, two samples from the superjacent Domengine and one from the subjacent Moreno (Cretaceous), both non-conformable to the Lodo.

A sketch map of the type area and a column show the position and make-up of the type section. The author states the upper 900 feet consist of gray silt and claystones; the lower 200± feet of claystones with interbedded sands and shales, with glauconitic sands at the base.

There are listed 129 previously figured foraminifera with their over-all range and a reference to the figures with which specimens are compared. These are not refigured. Thirty species and two subspecies are described as new, and well illustrated, four of the plates being the usual excellent work of Margaret Hughes.

The author divides the formation into three faunal zones which shall here be referred to as A, B, and C, A extending from the top of the Lodo to 600 feet above the base, B from 600 feet above the base to 180 feet above the base, and C including the lower 180 feet.

To analyze the evidence it was necessary to draw up a chart using the author's lists and ranges. The zones appear arbitrary, but practical, the species exhibiting overlapping ranges. The lower, zone C, possesses a few species restricted to it, but most extend into zone B. Zone B contains the richest fauna, many of its species extending to varied degrees into zone C, and the overlying Domengine, but some restricted.

The author states (p. 97, last sentence), "An attempt to draw precise conclusions regarding the age relationships of the Lodo Foraminifera, however, at such an early stage of paleontologic research, would be presumptuous." Nevertheless, we shall presume.

Let us first consider relationships to other West Coast foraminiferal faunas. The lower part of zone C is almost barren and had best be omitted; the upper part may be included in B. Zone B shows unmistakable relationships to the Canoas siltstone faunule of Cushman and Siegfus,[2] there is a lesser relationship to the Marysville Buttes assemblage of Israelsky,[3] and still less with the Llajas faunule of Cushman and McMasters,[4] and hardly any sugges-

[1] By permission of W. H. Spears, general superintendent, geology and land, Union Producing Company, Shreveport, Louisiana. Review received, August 20, 1943.

[2] J. A. Cushman and S. S. Siegfus, *Trans. San Diego Soc. Nat. Hist.*, Vol. 9, No. 34 (October 1, 1942). This article had not appeared when Miss Martin's paper went to press.

[3] M. C. Israelsky, *Proc. Sixth Pacific Science Congress*, Vol. 2 (1939), pp. 569–95.

[4] J. A. Cushman and J. H. McMasters, *Jour. Paleon.*, Vol. 10, No. 6 (September, 1936), pp. 496–517.

tion of the Markley of Church.[5] It seems certain this B zone assemblage and the Canoas belong in the same stage, as Schenck advocates that term. This is probably zone C of Laiming.[6]

Zone A contains numerous relicts from zone B, plus some low-ranging Llajas (Cushman and McMasters) species, besides a few peculiar to it. From the view of the subsurface worker it is more advantageous to include this zone with the Lodo than with the Llajas "stage." From the evidence offered by column and map this seems also logical for cartographic purposes. Either in this zone, or between it and the Llajas, probably the latter, is where the Marysville assemblage might be expected to fall.

In comparison with the Gulf Coast of the United States and Mexico the check list shows abundant relationships with the Gulf Coast Eocene, Midway through Jackson. In spite of numerous Claiborne and Jackson species, it is believed most Gulf Coast micropaleontologists would place zone B in the Midway-Wilcox (lower Eocene of the U.S.G.S.). To Gulf Coast eyes the presence of *Robulus pseudocostatus* (Plummer) in zone A above *Marginulina asperuliformis* Nuttall in zone B is disturbing, being an inversion of the Gulf Coast positions. In spite of this and other conflicting evidence, the reviewer regards, at least for the present, zone B of the Lodo as Wilcox in age.

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ARGENTINA

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ARKANSAS

*"Engineering Features of the Shuler Field and Unit Operation," by H. H. Kaveler. *Petroleum Technology*, Vol. 6, No. 4 (Amer. Inst. Min. Met. Eng., New York, July, 1943). 28 pp., 17 figs. *A.I.M.E. Tech. Pub. 1605.*

CALIFORNIA

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GENERAL

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[5] C. C. Church, *Mining in California*, State Min. Rept., Vol. 27, No. 2 (April, 1931), pp. 202–13.

[6] Boris Laiming, *Proc. Sixth Pacific Science Congress*, Vol. 2 (1939), pp. 535–67. *California Div. Mines Bull. 118*, preprint, Pt. 2 (August 1941), pp. 193–98.

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*"Proven Reserves Continue Decline with Important Discoveries in Three Areas," by W. V. Howard. *Oil and Gas Jour.*, Vol. 42, No. 12 (Tulsa, July 29, 1943), pp. 90–92, map and 2 charts.

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*"Manpower Shortage Imperils Industry's Exploratory Work," by A. R. McAtee. *Oil Weekly*, Vol. 110, No. 9 (Houston, August 2, 1943), pp. 20–22.

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IDAHO

*"Structure and Stratigraphy of Part of the Bannock Range, Idaho," by John C. Ludlum. *Bull. Geol. Soc. America*, Vol. 54, No. 7 (New York, July 1, 1943), pp. 973–86; 3 figs.

NEW MEXICO

*"The Galisteo Formation of North-Central New Mexico," by Charles E. Stearns. *Jour. Geol.*, Vol. 51, No. 5 (Chicago, July-August, 1943), pp. 301–19; 10 figs.

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TEXAS

*"Geology of the Northern Quitman Mountains, Trans-Pecos Texas," by Roy M. Huffington. *Bull. Geol. Soc. America*, Vol. 54, No. 7 (New York, July 1, 1943), pp. 987–1048; 3 pls., 6 figs.

VENEZUELA

*"The Rio Cachiri Section in the Sierra de Perija, Venezuela," by R. A. Liddle, G. D. Harris, and J. W. Wells. *Bulletins of American Paleontology*, Vol. 27, No. 108 (April 6, 1943). 100 pp., 10 pls., sketch map and geologic section. Paleontological Research Institution, 128 Kelvin Place, Ithaca, New York.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 27, NO. 9 (SEPTEMBER, 1943), PP. 1273-1278

THE ASSOCIATION ROUND TABLE

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The list of Association Committees, with the names of the chairmen and the members, is published in the June *Bulletin*, pages 876–78.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

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Holmes, Vernon E, Lane-Wells Co., Box 5113, Farley Station, Oklahoma City, Okla.
Hutcheson, R. Bellenden, The Superior Oil Co., Box 1031, Bakersfield, Calif.
‖Hutchins, Robert Morris, Jr., Stanolind Oil and Gas Co., Houston, Tex.

‖Jacques, Arthur N., 3015t College Training Detachment (Air Crew), State Teachers College, Eau Claire, Wis.
Janovy, Frank, Ptak Petr. Co., 502 Hales Bldg., Oklahoma City, Okla.
‖Jeffords, Russell M., U. S. Geological Survey, Box 854, Morgantown, W. Va.
Jones, I. W., Department of Mines, Parliament Bldg., Quebec, P. Q., Canada
Kallina, Frank Cyril, Continental Oil Co., Mission, Tex.
‖Kassander, A. Richard, Jr., 1 Lookout Circle, Larchmont, N. Y.
‖Kate, Frederick Henry, Shell Oil Co., Inc., Box 476, Centralia, Ill.
‖Kendall, Richard G., The California Co., 618 Simpson Bldg., Ardmore, Okla.
‖Kern, Jack Charles, Jr., 4311 Cedar Springs Rd., Dallas, Tex.
‖Kirkpatrick, Darrel L., 208 Watoma Ave., Santa Barbara, Calif.
Lamb, Noel Raymond, Continental Oil Co., Box CC, Hobbs, N. Mex.
La Neve, R. O., Trumter Petr. Corp., Box 1719, Fort Worth, Tex.
Lang, Joseph Winford, U. S. Geological Survey, Pecos, Tex.
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‖Leavitt, William B., Amerada Petroleum Corp., 1811 Niels Esperson Bldg., Houston, Tex.
Lee, Thomas William, Sagamore Oil and Gas Co., Independence, Kan.
Leyds, Louis W., c/o Asiatic Petroleum Co., St. Helens Court, Great St. Helens, London E.C. 3, England
‖Mann, John F., Jr., Frontier Refg. Co., Golden, Colo.
‖Marble, Kennedy R., Carter Oil Co., Box 801, Tulsa, Okla.
‖Martin, Robert Henry, The Texas Co., Box 299, Salem, Ill.
‖McCall, Charles L., 924 Ratcliff St., Shreveport, La.
‖McCall, John Edmund, Standard Oil Co. of California, Box 1528, Stockton, Calif.
McCluer, R. D., Exploracion Department, Petroleos Mexicanos, Tampico, Tamps., Mexico
‖McConnell, Robert B., Carter Oil Co., Box 1188, Sheridan, Wyo.
‖McDowell, Alfred Norman, 3001 Wood St., Texarkana, Tex.
McGee, John Evan, Gulf Research and Development Co., Drawer 2038, Pittsburgh, Pa.
‖McGrew, Harry J., Gulf Research and Development Co., Box 2038, Pittsburgh 30, Pa.
McLaughlin, Thad G., U. S. Geological Survey, Lawrence, Kan.
McMahon, Joe Trees, Benedum-Trees Oil Co., 311 First National Bank Bldg., Shreveport, La.
‖McNally, Perry Michael, Phillips Petr. Co., Bartlesville, Okla.
‖Miller, Richard F., 1105 S. Fillmore, Denver 10, Colo.
Monaghan, Richard Joseph, c/o S. A. P. Las Mercedes, Apt. 1429, Caracas, Venezuela, S. A.
Moore, Horatio L., J. E. Crosbie, Inc., 1810 National Bank of Tulsa Bldg., Tulsa, Okla.
‖Moore, Joe Laurence, Honolulu Oil Corp., Drawer 1391, Midland, Tex.
Moore, William Willard, Jr., 2015 W. Alabama St., Houston, Tex.
Mosher, William Nelson, Standard Oil Co. of Texas, Houston, Tex.
Nygren, Walter Eric, Standard Oil of California, 225 Bush St., San Francisco, Calif.
‖O'Boyle, Charles C., Heiland Research Corp., Golden, Colo.
‖Perko, Albert Richard, Texas Petr. Co., Apt. 877, Bogota, Colombia, S. A.
Perryman, James Dale, Geotechnical Corp., 1702 Tower Petroleum Bldg., Dallas, Tex.
‖Pettit, Albert Edwin, Hamilton Gas Corp., Box 2387, Charleston, W. Va.
‖Pirkle, E. C., Jr., Pan-Electronics Laboratory, Decatur, Ga.
‖Portis, Richard Wayne, Fairfax, Mo.
‖Ralstin, James Franklin, 5639 W. Maple, Wichita, Kan.
Ramsden, Charles Hugo, Richmond Petr. Co. of Colombia, Apt. Nac. 2760, Bogota, Colombia, S. A.
‖Reavis, George David, 622 N. Park, Shawnee, Okla.
‖Renfro, Millicent Aloyse, The Texas Co., Fort Worth, Tex.
‖Rhodes, Mary Louise, 508 N. Pecos, Midland, Tex.
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‖Ries, Edward Richard, Carter Oil Co., Freeman, S. Dak.
Roberts, Marion Stanton, Humble Oil and Refg. Co., Geismar, La.
‖Roberts, Price E., Box E-4, Pincher Creek, Alta., Canada
Rogers, Reginald Douglas, Jr., South Pennsylvania Natural Gas Co., Parkersburg, W. Va.
‖Rowe, Ural A., General Geophysical Co., 2514 Gulf Bldg., Houston, Tex.
Rubey, William W., U. S. Geological Survey, Washington 25, D. C.
Sasse, Jerome B., Apt. 32-B, 3839 Rodman, N. W., Washington, D. C.
Schnurr, Cornelius, Petroleum Administration for War, Box 2584, Houston, Tex.
‖Schweers, Frederick Paul, The Texas Co., Box 539, Ardmore, Okla.
‖Senning, Robert Conrad, Republic Natural Gas Co., 1505 Federal St., Dallas, Tex.
‖Shaeffer, Stanley Beaubien, 1647 Davis Ave., Whiting, Ind.
Shoemaker, William Morris, Forest Oil Corp., 577 E. Main St., Bradford, Pa.
Shugart, Thomas R., 1004 E. Broadway St., Fort Worth 3, Tex.
Siberts, Carl Edwin, Kingwood Oil Co., Evansville, Ind.
Simian G., Eduardo, Corporacion de Fomento de la Produccion, Punta Arenas, Chile, S. A.
‖Sims, Paul Kibler, U. S. Geological Survey, Metaline Falls, Wash.
‖Smith, Beverly Lorraine, Richfield Oil Corp., 560 Haberfelde Bldg., Bakersfield, Calif.
‖Smith, George Wendell, Magnolia Petr. Co., Box 1828, Oklahoma City, Okla.

‖Smith, Stanley Laurence, The Atlantic Refg. Co., Box 1346, Houston, Tex.
Snider, Clark Thomas, Lario Oil and Gas Co., Box 427, Mount Vernon, Ill.
Sprague, William B., R. F. D. #1, Whitingham, Vt.
Stones, James Eugene, The Superior Oil Co., Box 247, Seminole, Tex.
‖Swirczynski, Richard Paul, 1401 N. E. Twelfth St., Oklahoma City 4, Okla.
Swords, Henry Leonard, 3141 B McKinley Blvd., Sacramento, Calif.
Thalmann, Hans E., International Petr. Co., Ltd., Box 803, Guayaquil, Ecuador, S. A.
Todd, James Hopkins, The California Co., 1818 Canal Bldg., New Orleans, La.
Tottenham, Woodson Miller, Magnolia Petr. Co., Box 900, Dallas, Tex.
‖Travis, Russell Burton, Forestville, Calif.
‖Turner, Clyde Weldon, Gulf Oil Corp., Box 1290, Fort Worth, Tex.
‖Turner, Dale Edward, Box 899, Madera, Calif.
Vorbe, Georges, Department of Geology, New Mexico School of Mines, Socorro, N. Mex.
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Walters, Robert F., Gulf Oil Corp., Box 661, Tulsa, Okla.
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Wells, Robert Jackson, Richfield Oil Corp., 560 Haberfelde Bldg., Bakersfield, Calif.
‖White, William Harris, Division of Geology, G-5 State Office Bldg., Nashville, Tenn.
‖Whitney, Fred L., General Delivery, Conrad, Mont.
‖Willard, Max Emery, U. S. Geological Survey, Washington 25, D. C.
‖Williams, George Arthur, 212 S. Zinc St., Deming, N. Mex.
‖Williams, John Blaine, 2514 Stanmore, Houston, Tex.
‖Wilson, Charles Lewis, 405 S. First St., Austin, Minn.
‖Wilson, George M., State Geological Survey, 414 Natural Resources Bldg., Urbana, Ill.
‖Wolcott, Richard Hastings, Sohio Prod. Co., Mount Pleasant, Mich.
Wolf, George H., Shell Oil Co., Inc., Box 1191, Tulsa, Okla.
Wolff, Deane J., Magnolia Petr. Co., Box 900, Dallas, Tex.
‖Wolfram, Bertram, Jr., 1930 Forty-first St., Galveston, Tex.
Yoder, George M., Schlumberger Well Surveying Corp., Box 131, Jackson, Miss.
Young, John A., Jr., Michigan State College, East Lansing, Mich.
‖Yzaguirre Lauro Antonio, 307 W. Twenty-sixth St., Austin, Tex.

SIDNEY POWERS MEMORIAL MEDAL FUND

A. RODGER DENISON[1]
Tulsa, Oklahoma

The announcement of the establishment of the Sidney Powers Memorial Medal Fund reached our membership about June 15. By July 15 a total of $2,966.50 had been received from 411 contributors, thus giving the fund an early vigorous start. By August 15 the fund had grown to $3,754.50 contributed by 471 members and others.

The Medal Fund has had a wide appeal since, as here indicated, we have received contributions from 33 states, the District of Columbia, and 7 foreign countries. An outstanding feature of the donations is the fact that more than a few have come from men now in the Armed Services of our country.

While the early response has been satisfactory, and the interest is widespread, we have need for participation by many more members. On June 1, 1943, the Association membership was 4,007; thus a little more than 11 per cent of our members had made their contributions by August 15.

TABULATION OF DONATIONS BY STATES
August 15, 1943

Alabama	4	Massachusetts	4	Utah	2
Arkansas	1	Michigan	8	Virginia	4
California	49	Minnesota	3	Washington	2
Colorado	5	Mississippi	4	West Virginia	5
Connecticut	2	Missouri	4	Wisconsin	1
District of Columbia	16	Montana	5	Wyoming	1
Florida	1	New Jersey	2	Canada	5
Georgia	1	New Mexico	8	Chile	1
Illinois	14	New York	23	Colombia	2
Indiana	6	North Carolina	1	Cuba	1
Kansas	12	Ohio	6	Dominican Republic	2
Kentucky	2	Oklahoma	85	Hawaii	1
Louisiana	20	Pennsylvania	8	Mexico	3
Maryland	1	Texas	146	Total	471

[1] Chairman, medal award committee.

Herewith is a tabulation of total contributions classified according to the number which gave various amounts. This indicates that contributions ranged from $1 to $100 and the average was $7.97. As was indicated in the first announcement, the fund could be raised if *every member* gave $2.50. While it is the desire of the committee to build the fund from a large number of contributions, it is realized that we can never obtain response from the entire membership. It is then a source of satisfaction to find that a majority of contributors sent in more than the "minimum" amount.

TABULATION OF CONTRIBUTIONS BY AMOUNTS

August 15, 1943

11	$100.00	$1,100.00	1	3.50	3.50
5	50.00	250.00	23	3.00	69.00
18	25.00	450.00	187	2.50	467.50
3	20.00	60.00	8	2.00	16.00
3	15.00	45.00	2	1.50	3.00
65	10.00	650.00	21	1.00	21.00
123	5.00	615.00	—		
1	4.50	4.50	471		$3,754.50

GEOLOGISTS WILL BE DEFERRED FROM MILITARY SERVICE

K. C. HEALD[1]
Pittsburgh, Pennsylvania

The War Manpower Commission has now recognized that the shortage of geologists and geophysicists is so acute "as to impede or threaten to impede war production." It has also recognized that the science of geology requires long training and experience if good results are to be insured, and that experienced men therefore can not be replaced by simply promoting apprentices and assistants.

Geologists and geophysicists are included in the list of 149 critical occupations which has just been issued by the War Manpower Commission. Men possessing these skills and working for an essential industry have a first priority draft-deferment classification. The petroleum industry is an essential industry.

Under these instructions local boards should promptly defer geologists who are classified as 1-A, provided the employers of these geologists request such deferment. If the local board does not grant the deferment the decision should immediately be appealed and reference to the instructions from the War Manpower Commission should insure the appeal being granted. If both the Draft Board and the Appeal Board prove unable or unwilling to understand and apply these instructions, telegraphic appeal to the State Director of Selective Service, stating the conditions and requesting that he review the case should insure reversal of the lower decisions.

Recognition by the War Manpower Commission of the critical situation that has resulted from the persistent and heedless drafting of geologists and geophysicists is due, in great measure, to the intelligent, persistent, and undiscouraged efforts of president Denison and past-president Heroy.

[1] Chairman, national service committee.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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Memorial

JOHN W. REISS
(1920–1943)

First Lieutenant John (Jack) W. Reiss was killed in South Wales in the European area, June 4, 1943. Letters from General George C. Marshall and General H. H. Arnold praised his excellent record at each training field and his reputation for being a very capable and zealous officer, performing his duties so efficiently that he won the confidence of his superiors and the respect of his associates.

John Reiss was born, November 11, 1920, in Belleville, Illinois. He was the eldest son of the late Lieut. Colonel Walter J. Reiss and Mrs. Estelle E. Reiss, 1810 Santa Fe Street, Corpus Christi, Texas. His father served overseas during World War I in the Engineering Corps and was general superintendent of transportation at Bordeaux, France. He was cited for conspicuous and meritorious service and was awarded the Order of the Purple Heart.

One brother, Patrick F. Reiss, a chemical engineering student at the University of Texas, is now with the Army Specialized Forces Reserve Training Corps at Camp Maxey, Paris, Texas, while a younger brother, Bill Reiss, is a senior at Corpus Christi High School.

Jack Reiss attended elementary school at Laredo, Texas. He moved to Corpus Christi, Texas, in 1936, with his mother and two younger brothers, graduating from Corpus Christi High School in 1938. He entered the University of Texas in the fall of 1938, where he majored in geology. He completed his college work in 3 years, receiving his Bachelor's Degree in May, 1941. His extra-curricular work included membership in Triarthrus, geological society; The Newman Club; Eta Phi Upsilon; fencing society; and presidency of the Corpus Christi Club.

During the time Jack was in High School, he was employed by geologists with the Transwestern Oil Company and the Trinity Oil Company to assist in assembling district files for newly opened offices in this area. While attending the University of Texas, he worked in the office of R. W. Byram and Company.

While attending the University, Lieutenant Reiss enrolled in the C.A.A. flying course, receiving his pilot's license in August, 1939, and later completed his training in Advanced Civilian Pilot Training just before joining the Army Air Corps.

As a member of Class 42-H he received pre-flight training at Kelly Field Replacement Center; Primary at Victory Field, Vernon, Texas; Basic at Randolph Field; and Advanced at Foster Field, Victoria, Texas, where he was commissioned a Second Lieutenant on September 6, 1942. During his training at each field he was elected Cadet Lieutenant and at Randolph Field he also served as Battalion Adjutant on the Battalion Staff.

Jack was promoted to First Lieutenant on January 20, 1943, and had been recommended for a Captaincy shortly before his death. Before going overseas he had been appointed Operations and Executive Officer of his squadron, which post ordinarily carries the rank of Major. Up to the time of his death, he was also filling the position of Supply Officer. He was pilot of a twin-engine bomber, the Martin B-26 (Marauder).

Jack became an associate member of the Association in 1941, sponsored by Fred M. Bullard, Robert H. Cuyler, and Hal P. Bybee.

In June, 1941, he was employed by the Stanolind Oil and Gas Company in Houston, Texas, as a geologist, until he resigned to join the United States Army Air Corps.

His record speaks for itself. He was an exceptional character. His former friends and associates sadly regret that the Association has lost a member of whom it was justly proud. The geological profession will surely feel the premature loss of such young men as Jack Reiss.

FRITH C. OWENS

CORPUS CHRISTI, TEXAS
July, 1943

GEORGE C. MARTIN
(1875–1943)

The death of George C. Martin on June 22, 1943, at the age of 67, marks the passing of one more of the geologists who did much in the pioneer days to furnish a sound basis of fact on which the present knowledge of the geology of Alaska has been built.

Born in Cheshire, Massachusetts, July 18, 1875, he graduated from Cornell with a degree of B.S. in 1898, and from Johns Hopkins in 1901, with a degree of Ph.D. While at Cornell he was given leave of absence to assist the Philadelphia Academy of Natural Science in cataloging and arranging the Society's collection of Eocene fossils. Later at Johns Hopkins he served as assistant and instructor until 1903, and during much of that period also carried on field investigations as assistant and geologist of the Maryland Geological Survey in areas that are especially significant for their coal resources. This training and experience gave him a background that brought him in 1903 to the favorable attention of Dr. Alfred H. Brooks, in charge of the Alaskan work of the Geological Survey,

who was on the lookout for someone to undertake the study of Alaskan coal and oil fields. Thus began Martin's active connection with the Alaskan work of the Geological Survey which lasted until 1924 when he resigned to enter private practice.

During his Alaska services Martin successfully made the first intensive examinations in various of the Territory's oil and gas regions as follows: in the Katalla and Controller Bay oil and coal fields (1903–1906); in the Matanuska coal fields (1905, 1910, and 1913); in

GEORGE C. MARTIN

the Kenai coal fields (1911); the Nenana coal fields (1916), and parts of the Alaska Peninsula oil fields (1903 and 1923).

The detailed knowledge obtained in the course of those expeditions was broadened by his participation in numerous other expeditions, including surveys in the Iliamna district in 1909, and in the Chitina-Yukon region in 1914. These all furnished fundamental data which led Dr. Martin to become increasingly committed to a comprehensive analysis and correlation of all of the Mesozoic stratigraphy of the Territory. To this major research he devoted all of his spare time during the rest of his Survey career and it called for his undertaking additional field surveys to cover parts of the Iditarod, Innoko, and Kuskokwim regions in 1920, and the western Yukon and Koyukuk regions areas in 1921. The completed

report entitled "The Mesozoic Stratigraphy of Alaska," published in 1926 as United States Geological Survey *Bulletin 776*, is an exhaustive scholarly study of all information available to the author and the knitting of that information into a coördinated interpretation of the many diverse facts so that they fitted into a working standard section of the enormous thicknesses and variations of the Mesozoic formations. The importance of the study of this sequence of rocks in Alaska is perhaps best realized by the following statement from Martin's own report.

> These strata are of extreme interest not only because they occupy so large a part both of the area and of the stratigraphic section of Alaska . . . but because they show significant relations with the known sections in other regions and because they will, when thoroughly studied, undoubtedly be found to constitute one of the most complete sections of much of the Mesozoic, especially of the Jurassic and Upper Triassic rocks in North America if not in the world.

Necessarily the information regarding many of the Mesozoic formations was at that time adequate for drawing only tentative conclusions and some of the suggested correlations then made have subsequently been shown to fit better other interpretations. On the whole, however, the work has stood well the tests to which it has been subjected in the past 17 years and is an enduring memorial to its author.

Martin's regular geologic duties in the Alaskan Branch were interrupted in 1912 by his being chosen to head an expedition of the National Geographic Society[1] to investigate the eruption of Mt. Katmai, Alaska, which in June of that year had broken out with devastating violence. Within a month he was on the ground retraversing the area with which certain of his earlier expeditions had made him familiar, and collecting an interesting record of the events attendant upon and following the eruption.

Martin's own scientific work on the Survey was also frequently interrupted by his being called upon to assume administrative responsibilities in the absence of the chief, Alfred H. Brooks. Thus in 1912, when Brooks was serving as vice-chairman of the Alaska Railroad Commission to select a suitable route for a governmental railroad to link the coast with Interior Alaska, the general running of the Branch was placed on Dr. Martin. Again, in 1917 to 1919, while Colonel Brooks was abroad in service with the American Expeditionary Forces, the administration of the Branch was successfully handled by Dr. Martin.

In July, 1924, Martin's long and varied career in the Alaskan Branch was terminated by his resignation to undertake the commercial practice of his profession in the oil industry. Records are not available to the writer as to the specific jobs he undertook during this period of private practice which lasted until 1935, but they included work in Mexico, British Columbia, and the southern Atlantic states, and during part of the time he made his home in Eugene, Oregon.

In 1934 the duties and responsibilities of the old Board on Geographical Names that had been designated by the President to coördinate and unify geographic names as used by the Government were redefined and the task transferred to the supervision of the Secretary of the Interior. Search for a man who would serve as the continuing official to prepare the various cases for consideration and who would carry out the decisions of the Board led to the selection of Dr. Martin for the post as executive secretary. Dr. Martin was eminently qualified for this work by his long familiarity with the use of maps and by the basically research attitude with which he took up all problems calling for the meticulous search for all available facts and the thoughtful analysis of conflicting data. In this search he not only utilized fully available libraries and map collections but also for the first time introduced field work in checking locally the source and usage of geographic names in conflict. In his position as executive secretary, Martin served well and conscientiously up to within a few months of his death, though a few years before in the course of his

[1] *National Geographic Magazine* (February, 1913).

field work in Mexico or the West he may have incurred some obscure infection or disease which so undermined him physically that his friends felt that he should then have relaxed and devoted himself to recovering his health.

Personally he had a mixture of the individualistic New Englander with much of the latter's outward austerity and self repression and lack of general sociability superimposed on the precision and exactness of the critical scientist. These characteristics resulted in his developing into more or less of a lone worker and prevented his sharing or participating in some of the intimacies and lightsomeness that build up close personal friendships. Never of a rugged physical build, it is astonishing the stamina and resiliency he showed in carrying through many of the difficult assignments that fell to his lot in the days when field work in Alaska could be accomplished only by the expenditure of a great outlay of mere muscle and brawn. The death of his wife intensified his aloneness until his daughter, Louise Martin Harrington, devoted herself to the management of his home. She and his son, William E. Martin, a trained botanist, now on an Agriculture Department mission in South America, and in whom he rightfully took great pride, were his only living children. His brother, Colonel Lawrence Martin, chief of the Division of Maps in the Library of Congress, is the only other near relative surviving him.

Dr. Martin was a member of the American Association of Petroleum Geologists and was always keenly interested in the activities of that organization. In addition, he belonged to a number of scientific, technical, and professional societies, among which may be mentioned the Geological Society of America, the National Geographic Society, and the Geological Society of Washington.

PHILIP S. SMITH

UNITED STATES GEOLOGICAL SURVEY
WASHINGTON, D. C.
August 10, 1943

OTTO FISCHER
(1877–1943)

The friends of Otto Fischer were deeply grieved by the news that he suddenly passed away in Charleston, West Virginia, on June 22, 1943.

He was born in Werdt, Canton Berne, Switzerland, on July 18, 1877, of typical mountaineer stock. True to tradition, he was a great lover of the mountains and in his college days he was a prominent member of the Academic Alpine Club.

His father was a school teacher and Otto also chose the teaching profession, attending Normal School at Berne. After this he taught for 2 years at the grade school of Guttannen, a village in the Bernese Oberland.

His fondness of nature and his interest in the rocks forming the mountains he so loved led him to study geology first at the University of Berne, where he acquired a diploma for high-school teaching, and then at Zurich. He received his Ph.D. degree from the University of Zurich in 1904. His specialization was in petrography, but his knowledge was based on a very broad foundation, so that later in life he could broach any problem with great facility.

After graduation he taught at the high school in Aarau, Switzerland, from 1904 to 1913. During vacations he also worked for the Swiss Geological Survey. He married Miss Emmy Christ of Berne, in 1904, who made him a lovely home. They had two sons, Hans and Otto.

While he was a very much liked teacher and enjoyed this kind of work, he had the urge to see the world and in 1913 he came to the United States as geologist for the Union des Pétroles d'Oklahoma in Tulsa, Oklahoma. In 1915 he succeeded the writer as chief geologist for this organization. When this company later merged with the Crawford in-

terests he stayed with the newly formed Oklahoma Producing and Refining Company, but in 1919, when peace made travel again possible, he resigned to return to his family, who had stayed in Switzerland during the war.

Returning to the United States in 1920, he joined the writer in the consulting business first in Okmulgee, Oklahoma, and later in Tulsa. On our recommendation the Owens-Libbey Owens Gas Department in Charleston, West Virginia, was organized to furnish gas to the large glass factories of these firms in West Virginia. This business soon grew to the point where it needed a permanent geologist and the position was offered to Otto Fischer in 1922. He held it until his death. He was in charge of geology, engineering, and land

OTTO FISCHER

operations. Having only a small staff, which was further reduced on account of the war, he was always very busy. However, he enjoyed such a diversified occupation. His love of the outdoors kept him out at drilling wells and in the field much of the time. Another important and difficult job in this rough country was the location and survey of pipe lines. His energetic nature often brought him out first on the spot, if any trouble developed in the field and he knew his way around in this part of West Virginia better than most people.

Otto Fischer is survived by his widow and the two sons as well as a granddaughter. His desire was that his sons should go through the Swiss schools; therefore, he was separated from his family until this was accomplished. Then Mrs. Fischer joined him in Charleston, where they built a home high on the hill south of town. While both of the sons had visited their parents in this country, they are at present in Switzerland. Tentative plans to move to this country were spoiled by the outbreak of the war.

Otto Fischer loved to travel and see the country, especially where it is mountainous and where interesting geological features can be observed. He visited much of the Alps as well as other parts of Europe, most of the United States, also Canada and Mexico, telling of his travels and exhibiting pictures, since he was an expert photographer. He was also a great lover of music and enjoyed playing the piano.

He was a member of the A.A.P.G. since 1917 and a member of the A.I.M.E., also of the Tulsa Geological Society from its beginning to the time he moved to West Virginia. There he was one of the founders and the first president of the Appalachian Geological Society and often drove home late after one of their meetings in Ashland, Kentucky, in order to be at his desk in the morning.

All of his friends and associates will remember him as a very energetic and interesting personality and a true friend, always ready with help and advice. As one of his Charleston colleagues expressed it: "The geological profession has suffered a severe loss in the death of Dr. Otto Fischer. He was a sound and able scientist in every respect and a good fellow and friend to all in the industry." Those who enjoyed his love and friendship will always gratefully remember the time spent in his company.

EDWARD BLOESCH

TULSA, OKLAHOMA
July 24, 1943

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

Major JOHN E. ELLIOTT has been transferred from Atlanta, Georgia, to become chief of administration of the Dallas Chemical Warfare Procurement Office. His address is 700 Mercantile Bank Building, 106 Ervay Street, Dallas, Texas.

E. R. MCFARLAND is employed by the Coralena Oil Company, Tulsa, Oklahoma.

DONALD M. DAVIS has left the United Geophysical Company, for whom he was geophysicist and party chief, and is now employed as geologist and geophysicist with the Richfield Oil Corporation, 560 Haberfelde Building, Bakersfield, California.

JOHN J. JAKOSKY, former dean of the School of Engineering and Architecture at the University of Kansas, has been appointed assistant to the president of the University of Southern California.

A. F. PETERSON, recently with the Ohio Oil Company, has joined the Mohawk Petroleum Corporation, Bakersfield, California.

W. A. J. M. VAN WATERSCHOOT VAN DER GRACHT, charter member (1917) and honorary member (1936) of the Association, died at Roermond, Holland, according to a recent Associated Press report from London. Dr. van der Gracht was president of the Roxana Petroleum Company (1917–1921) and vice-president of the Marland Oil Company (1922–1928). In 1932 he became director of The Netherlands Bureau of Mines.

M. T. HARTWELL, formerly with the Mid-Continent Petroleum Corporation, is manager of the West Texas and New Mexico areas for the Buffalo Oil Company, at Midland, Texas.

HAROLD E. VOIGT has joined the geological staff of the Superior Oil Company at Houston, Texas. He was formerly with the Phillips Petroleum Company.

CHARLES W. ROOP is geologist in charge of the district office of the Tide Water Associated Oil Company of Wichita, Kansas.

Major ALBERT S. CLINKSCALES, of Oklahoma City, Oklahoma, is at the School for Military Government at Charlottesville, Virginia.

Major HUBERT G. SCHENCK, of Stanford University, California, has finished the course at the School for Military Government at Fort Custer, Michigan.

E. DEGOLYER has resigned as assistant deputy administrator of the Petroleum Administration for War and has been appointed consultant to the newly organized Petroleum Reserve Corporation, a unit of the Reconstruction Finance Corporation. Secretary of the Interior Ickes is president of the new organization.

HARRY L. BALDWIN, who returned a few months ago from several years' work for the Y. P. F. in Argentina, is with the Phillips Petroleum Company, Bartlesville, Oklahoma.

ROY T. HAZZARD, of the Gulf Refining Company of Louisiana, discussed "The Upper Cretaceous-Lower Cretaceous Contact," at the first fall meeting of the Shreveport Geological Society, September 7.

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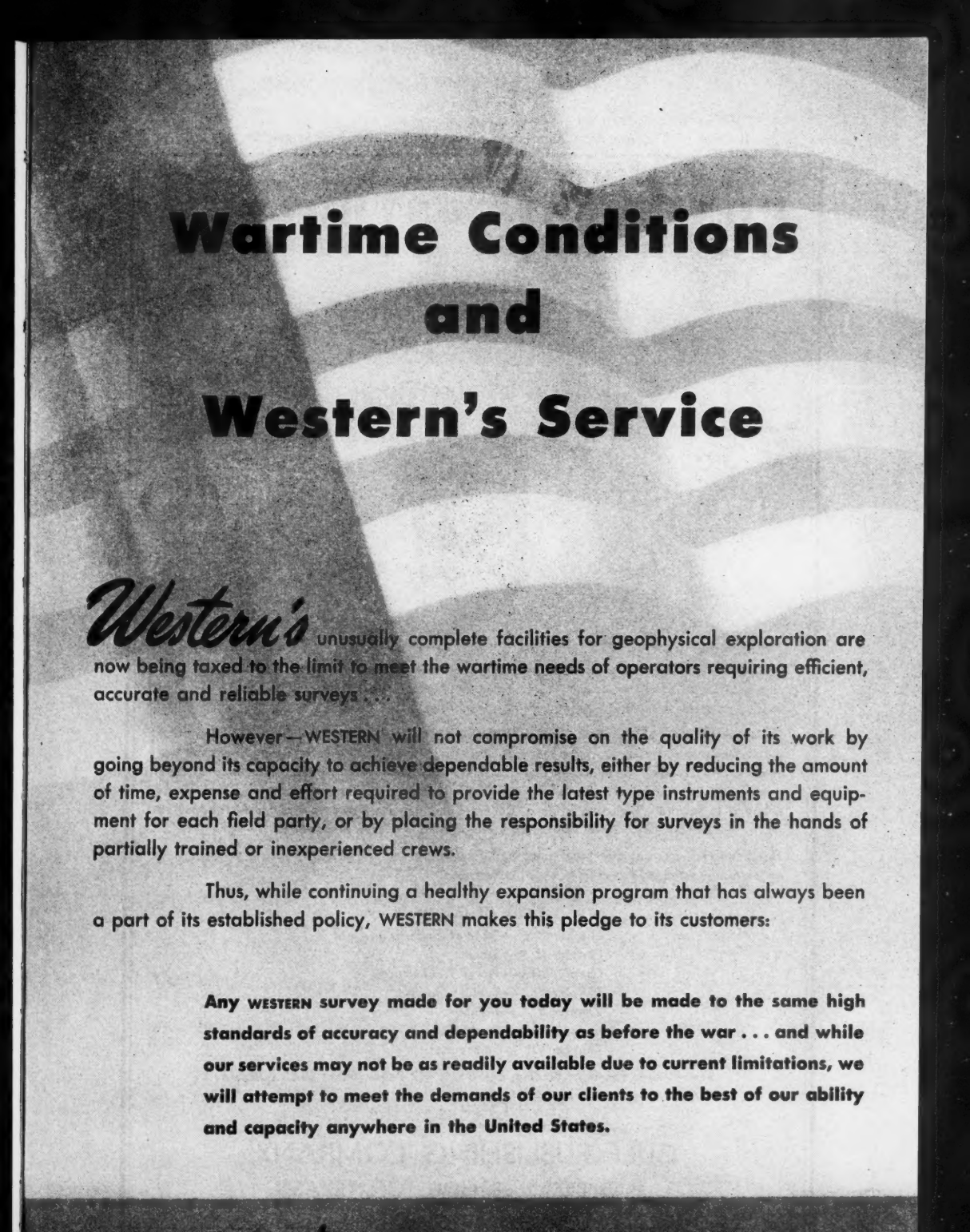

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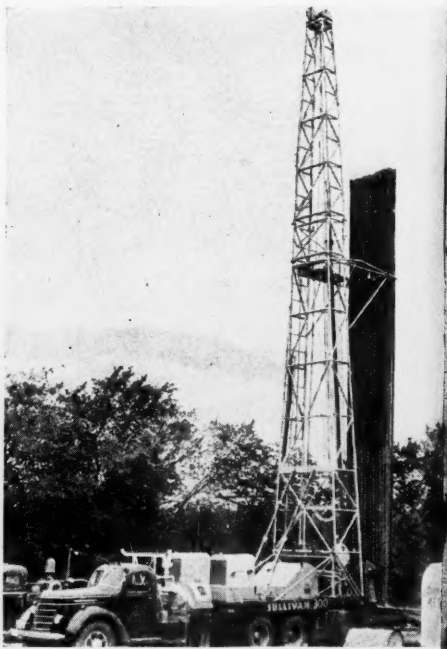

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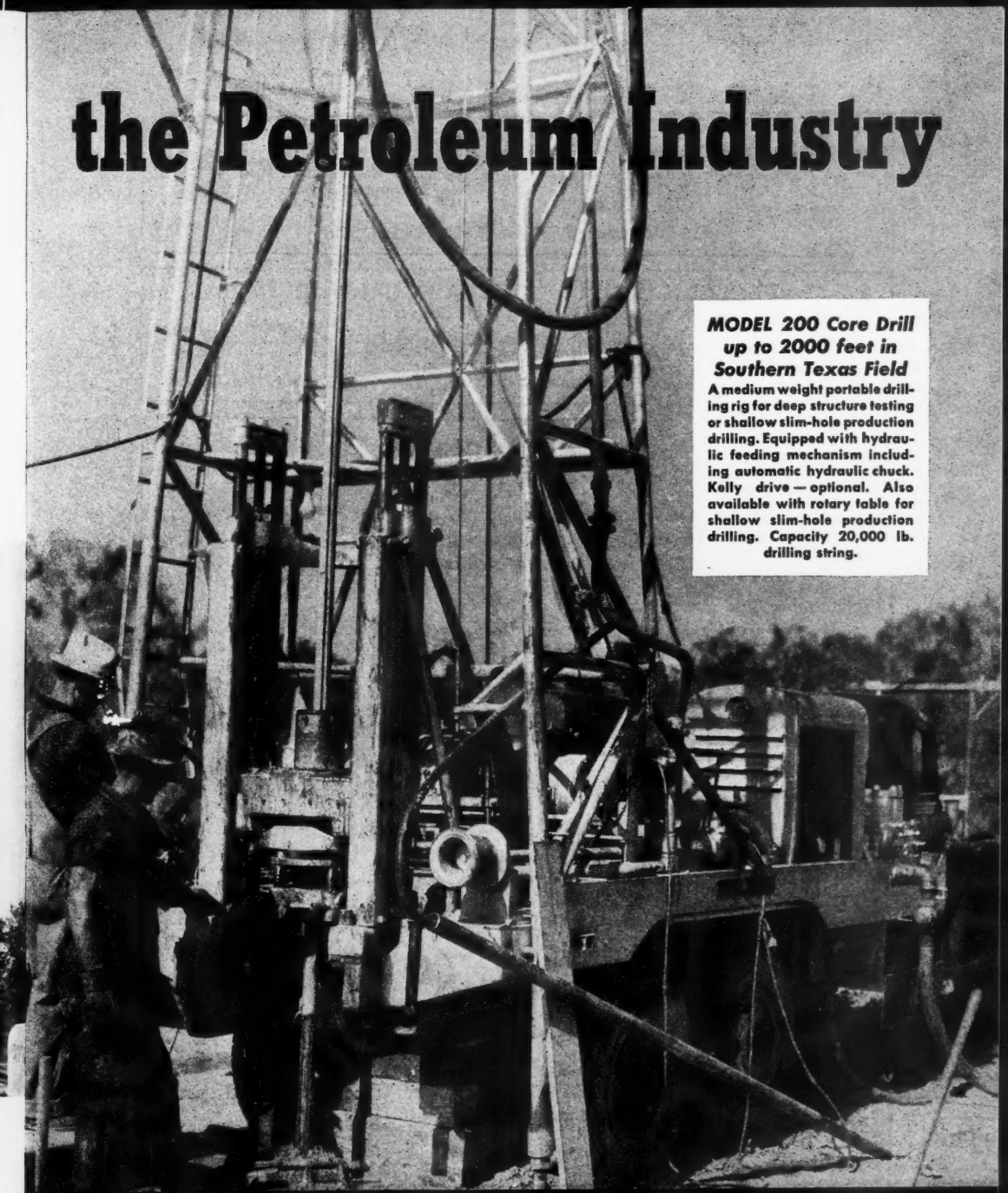

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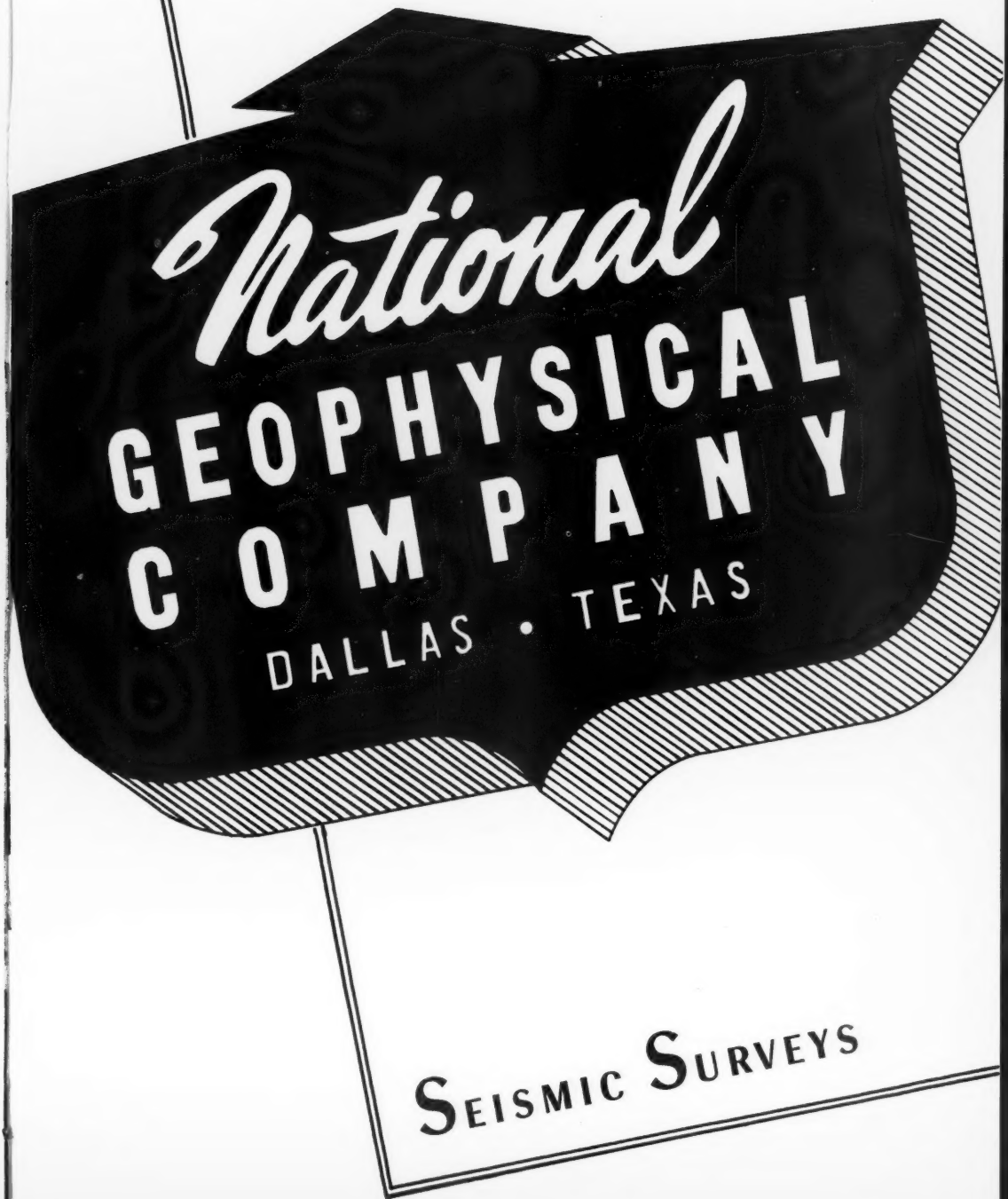
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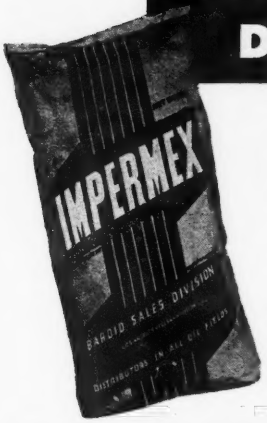

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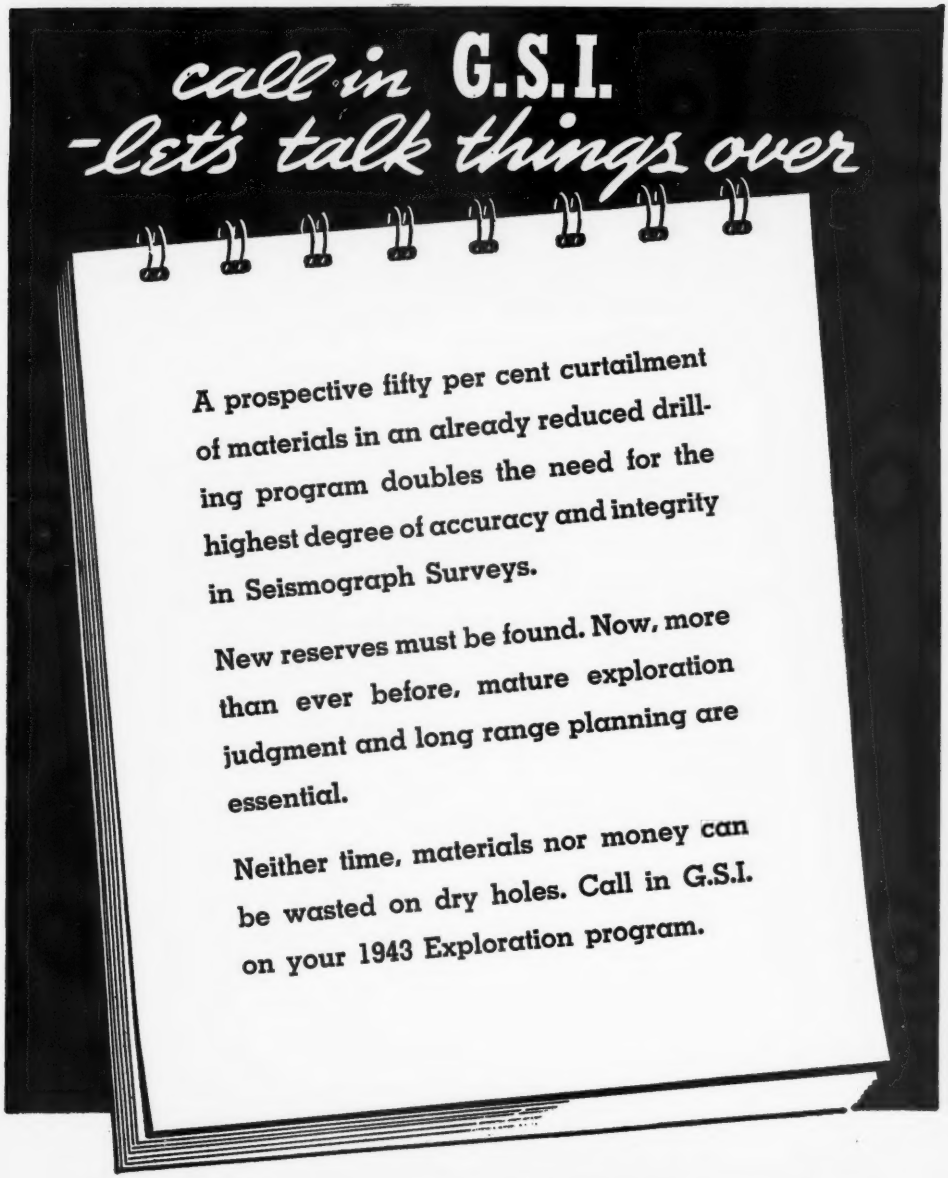
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